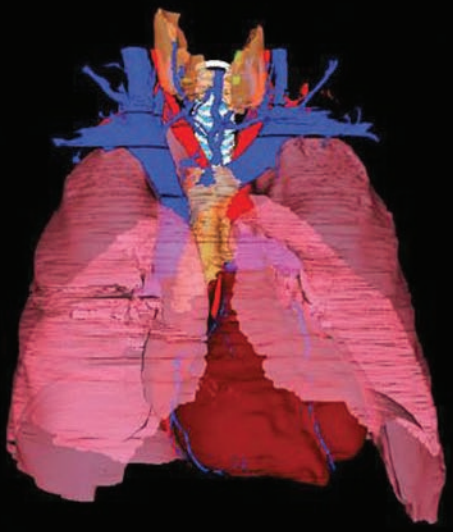
COMPLICATIONS IN CARDIOTHORACIC SURGERY

AVOIDANCE AND TREATMENT

2nd edition

Alex G. Little and Walter H. Merrill



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Complications in Cardiothoracic Surgery

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AVOIDANCE AND TREATMENT

Second Edition

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Alex G Little, MD

Likewise, I am grateful for the many teachers, mentors, and colleagues who have instructed, guided, and supported me during the course of my journey in cardiothoracic surgery. Working with students and residents has been a particular joy and privilege. Finally, I wish to acknowledge my indebtedness to the many patients who have taught me so much.

Walter H Merrill, MD

Preface

The reception of the first edition of this book has encouraged us to proceed with the development of this second edition. As before, we think of our book as a complement to the standard cardiothoracic surgery textbooks that address operative techniques and postoperative care. Acquisition of the information gained from the careful study of these books helps to establish the basic fund of knowledge that the thoracic surgery trainee and practitioner builds upon to establish final surgical competence. This knowledge foundation is supplemented by the real world experience with patients in the operating room, hospital, and clinic. It is this combination of knowledge and experience that leads to the development of the fully mature and capable thoracic surgeon.

We all are aware that this real world learning process involves the recognition of complications and the ability to learn from them. This is expressed in the common observation that good results come from experience and experience is acquired by making mistakes and learning from them. As before, the goal of our book is to minimize the frequency of surgical complications and maximize the patients' outcome when they do occur by allowing the reader to learn from the operative and clinical experience of those who have gone before. This means that each generation can learn and benefit from the experience already gained by others. There is no need for each of us to make our own mistakes or have our own complications if we can benefit from the experience and accumulated wisdom of others.

Therefore, this book and its chapters are focused on the issue of complication prevention and/or recognition and treatment. While the chapter authors have been asked to address the correct or standard way to perform operations and care for patients afterward, they have also been challenged to address and emphasize specific issues related to both intraoperative techniques and postoperative care that will reduce the incidence of complications. This is a slightly but importantly different focus from standard textbooks. As some complications are essentially inevitable, also addressed by the authors are the issues of timely recognition and appropriate treatment of complications when they do occur, despite best efforts to prevent them.

In summary, we hope that this book will serve as a useful supplement to, and not a replacement for, standard textbooks and operative atlases. We are confident that the readers will be representative of the proud tradition of a constant commitment to excellence in cardiothoracic surgery.

Alex G Little and Walter H Merrill

CHAPTER 1

Preventing Complications: New Frontiers of Safety Science in Cardiothoracic Surgery

Paul N Uhlig, William R Berry, Ellen Raboin, Jeffrey Brown, Joel T Erskin, Ann Hendrich and Daniel Raemer

This chapter is written by an interdisciplinary team of authors with experience studying and applying safety science in cardiothoracic surgery. Paul Uhlig is a cardiothoracic surgeon with special expertise in high reliability clinical teamwork. Bill Berry is a cardiothoracic surgeon whose full-time work concerns patient safety and risk management. Ellen Raboin has expertise in group processes and team interactions and special expertise in action research regarding teamwork and safety in health care environments. Jeffrey Brown is an aviation safety and human factors expert with extensive experience in implementing and studying teamwork in cardiac surgery and other health care settings. Joel Erskin is a cardiothoracic surgery physician assistant and former USAF pilot, safety educator, and hospital commander, who co-led early efforts to improve health care outcomes on the basis of principles of aviation safety. Ann Hendrich is a nationally recognized nurse executive and health care leader with expertise in transforming clinical care processes to improve safety and reliability. Dan Raemer is a biomedical engineer and leader in the field of health care simulation with expertise in critical event simulation and team training in cardiothoracic surgery. The chapter is written jointly from all of these perspectives.

In the same way as new approaches to cardiothoracic surgical operations are reshaping and transforming the specialty, new approaches for decreasing risk and improving patient safety are transforming the way that cardiothoracic surgical care is organized and practiced. This transformation is driving significant changes in surgical practice, education, and certification. Most importantly, it is producing better and safer patient care and a better experience of care for patients and practitioners alike.

Evidence supporting the effectiveness of these new approaches comes from pioneering studies in health care and from more fully developed research in

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other areas of high-risk human teamwork such as aviation, space flight, nuclear power plant operations, and similar high consequence human activities where safety has been extensively studied. For us, incorporating these new approaches into our own daily work has been a remarkable experience. As experienced clinicians and scientists familiar with previous methods for achieving quality and safety in healthcare, it seems evident to us that the new ways are significantly better than the ways in which we were trained. We believe that convincing data will follow. For us, it is impossible to go back.

Accordingly, this chapter is written somewhat differently than chapters in most surgical textbooks. It is an invitational summary of emerging concepts, intended to introduce you to new ideas and help you explore them in your own practice. We believe that as you consider these ideas and incorporate them into your work, you will find them to be as fascinating, surprising, and hopeful as they are for us.

Tuesday morning, 7:05 a.m.

Claire shoots a quick smile at Marilyn as the two women in surgical scrubs walk briskly toward the pump room between OR 29 and 30. Marilyn, the manager of OR cardiac nursing, has been here since 5:30 a.m. getting things ready for the day. As usual, Claire is running a little late, carrying her motorcycle helmet in one hand and her loupes in the other. "Good morning, Claire. You're in 29 today," says Marilyn, acknowledging Claire's smile. "The cine for your first case is up on the computer, but we're having a little trouble finding the H and P." "Thanks, Marilyn," says Claire, "I'll get it for you. The office must have forgotten to send it over last night."

An hour later, Claire has settled comfortably into her OR routine. Her iPod is docked and playing the third track of her opening playlist, a Ravel orchestration of Mussorgsky's Pictures at an Exhibition. The IMA is down and Claire is placing the last cannulation suture. As usual, the room is relaxed and happy. It always is for Claire's cases, Marilyn thinks to herself as she catches up on her charting in the computer.

"ACT is 300," says Dave. It has been at least 2 months since he has done an on-pump case with Claire, maybe longer, he thinks to himself. He is sure it has been at least 2 months, because that is how long the contract negotiations with the hospital have been going on. He sighs and shakes his head thinking about those negotiations. What a mess. As chief of perfusion services, the contract negotiations have occupied every nonclinical moment of his days and quite a few restless nights, too, for what seems like an eternity. Fewer on-pump cases, in fact fewer cases overall since the surgical group opened their own hospital 2 years ago. Dave is 58. He has been a perfusionist here since he finished training 30 years ago. Before that he was a respiratory therapist. So much has changed, he thinks to himself, as he sits down behind his pump.

Claire's voice interrupts his thoughts, "OK to clamp and cut?" Dave leans forward, accidentally bumping his clipboard, which falls to the floor. He reaches

down to retrieve the clipboard, turns off the arterial pump head, clamps several lines, and replies, "OK to clamp and cut." Claire watches Dave settle back into his seat. Marilyn is right, Claire reflects, remembering something Marilyn mentioned yesterday. Marilyn said that Dave didn't restock cannulas last week and seemed preoccupied. He is different somehow, Claire thinks to herself, not the same steady Dave who took me under his wing when I started here 4 years ago. Maybe I should talk to him sometime.

A few minutes later, Claire has finished cannulating. She double checks the aortic line for air and looks up at Dave. "Dave, you OK for going on?" she asks. Dave nods. Claire takes the clamp off the venous line. "On bypass please, Dave, drift to 34, keep the cardioplegia warm." Claire watches as dark red blood swirls into the venous line and drains toward the pump. She scans the field and watches the heart begin to empty. She thinks of her patient, Jim, a 40-year-old man with a bicuspid aortic valve. His LAD lesion had been a surprise. A new valve and one graft. Not a bad first case of the day.

Her mind flashes briefly to Jim's family. She said hello to them on the way to the OR. Tiffany, Jim's wife, had seemed so young. So had their four children. "Marilyn, can you let the family—," she begins, but stops in mid sentence as her eyes move across the field to the aortic line. "Dave, is everything OK? The heart's empty but I don't see any blood in the aortic line, just prime."

"I know," says Dave. "I can't flow. I don't know. . .Oh, here it is. No, that isn't it. I don't know. For some reason. . . I can't flow with the centrifugal pump. I'm changing to the backup pump head, the roller pump. It should take just a second."

Claire is aware of the clicking of clamps and a flurry of activity as Dave rapidly resets his pump. "Susan, I need that line clamp back," Claire says to her scrub nurse, "right now." Claire looks at the monitor and watches as the arterial pressure drops through 30. She scans the lines and surgical field, looking up across the drapes at John, the anesthesiologist, who is now at full attention at the head of the table. "Dave," Claire says, "I'm clamping the venous line here at the field. John, go into Trendelenberg and run whatever fluids you've got wide open. Marilyn, would you see if anyone is in the pump room? Maybe Shelly can come in and help Dave." Her heart sinks as she checks the arterial pressure again: 18 mm Hg and falling. Why didn't he flow in before draining out, she thinks to herself. We've talked about that before. She watches the lines warily for air and asks Susan for another line clamp, just in case.

"I've switched over, Claire. Coming up on flow now," says Dave. Claire feels a moment of relief as Dave opens a clamp and turns on the pump. What happens next will be etched in her mind forever. With a sudden, decompressive tearing sound a torrent of blood erupts from the pump, drenching Dave, turning the wall, the pump, and the ceiling red, and flooding the floor. Dave's face is covered with blood and he cannot see. His mask is saturated and sucks so tightly to his face that he cannot breathe. He pulls frantically at the mask and reaches blindly, desperately for his pump control. Somehow he shuts off the pump and the torrent stops.

Claire looks up at the monitor. The pressure has settled flat at 12 mm Hg. Her mind is racing to absorb the scene: blood everywhere, total confusion in the room, the empty heart still beating as if oblivious, steep Trendelenberg, John determinedly squeezing in some sort of crystalloid, her patient warm with no blood volume and no blood pressure.

In her mind's eye, as if in slow motion, she somehow sees Tiffany and the children sitting in the waiting room. Time changes and the door from the pump room opens. "Shelly! Thank God," Claire says. "See if you can help Dave. I don't know what happened but something just blew up. We've got no pressure, no volume, and the patient's warm. John, Shelly, think with me."

Pausing the action

Pause for a moment and reflect about what you are experiencing as you read this story. If we have done our job well as authors, you have hopefully been drawn into the story. It may have become real for you. As a surgeon, you may be imagining yourself in Claire's place, experiencing her stress and picturing what she should do next. Possibly, you have faced a similar situation in your career and could offer her advice.

This story is our attempt to show you the power of simulation in health care. Simulation is like a story brought to life. Throughout history, storytelling has been the main way that information has been passed among people. Even today, telling stories remains the most powerful form of communication. A well-designed simulation, like a good story, feels authentic. People in the simulation feel and act as if they are in a real situation.

We have paused our story to emphasize some important points about simulation and its value in helping people reflect about their actions in difficult situations. When actions can be paused, people often recognize things that are not evident when they are caught up in the flow of events. Much of the information within events is perishable, lost by the time the event is over. Simulation allows actions and perishable information to be captured, so that they can be reconsidered later.

Often the most important learning opportunity in simulation occurs after the simulation, when the people involved come together to review their experience (often recorded on videotape) and share their thoughts and observations in a debriefing. It is very helpful to have a trained facilitator guiding this conversation. It is often surprising to people how much their initial impressions of what happened can change as they see events unfold again, watch their own actions, and hear the perspectives of others.

Back to our story

In fact, this is a real story. Specifics of the case and the people have been changed. But the clinical situation happened exactly as the story describes.

What was the outcome? Working together, the surgical team recognized that enough blood was still present in the venous reservoir to restore an effective

blood volume. The challenge was how to get the blood from the reservoir back into the patient in the short time that was available, without a functioning pump or arterial line.

Recalling past research training, the surgeon remembered giving volume in the laboratory by pouring saline into a funnel connected to the right atrium suspended above the heart. The venous reservoir was like the funnel; all they had to do was somehow get it above the patient. The surgeon focused the attention of the team on this goal. Improvising, the perfusionists were able to detach the venous reservoir from the pump and lift it above the level of the heart, allowing blood to drain back into the patient. The patient's blood pressure normalized. After stabilizing the patient, cleaning the room, and changing out the pump, the rest of the operation proceeded uneventfully. The patient did well. After the operation, the patient and family were informed fully about the mishap and what was done.

What was the cause? The direct cause was an unrecognized clamp on the arterial line just downstream from the centrifugal pump head. The pump could not flow because of the clamp. The perfusionist switched to a backup roller pump that overpressurized the clamped arterial line and blew it out.

A deeper cause was distraction and fatigue of the perfusionist, a result of organizational circumstances. Contributing to the accident was a communications culture that led the nursing leader to "hint and hope" about changes she had noted rather than bringing her concerns openly and comfortably to the attention of the perfusionist and other team members. The communications culture also gave members of the team limited options for eliciting and responding to concerns in an effective way.

In this case, the outcome was good. Often when things go wrong, people are able to react and save the situation. Part of safety science deals with how to optimize crisis management. Another important part of safety science studies risk preconditions that can be proactively modified, making it less likely for an adverse event to occur. Most of the opportunities for transforming care are in this area.

As a result of this experience, procedural changes were adopted including test perfusion before initiating bypass, and establishing arterial inflow before opening the venous line. If you are thinking like a safety scientist, you recognize that these changes do not address many root causes of this accident.

The system approach to safety and the safety pyramid

James Reason, one of the pioneering thought leaders of the field of safety science, emphasizes that there are two ways to understand and achieve safety: the person approach and the system approach [1, 2]. From the person approach, the primary focus of the story above would be on the actions of the perfusionist and mistakes that were made by that person. The basic assumption of the person approach is that if something goes wrong, it is obvious that someone must be responsible.

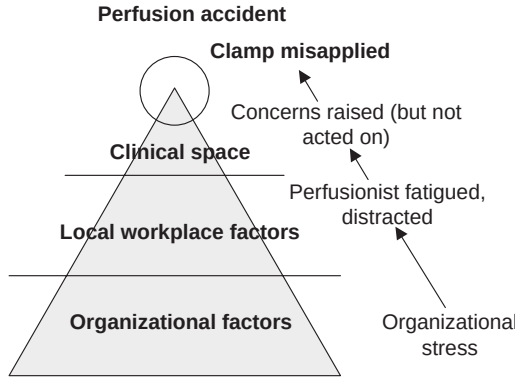

Figure 1.1 The safety pyramid. Events in the clinical space are influenced by factors, decisions, and actions at all levels (after James Reason [1]).

From the system approach, the primary focus shifts from the individual to the context in which people work. A basic assumption of the system approach is that people are fallible and that mistakes are inevitable. A further assumption is that errors usually have systemic causes. The goal is to build system defenses that increase the likelihood of safe outcomes. When adverse events occur, the question is not whether a mistake was made, but why defenses failed and how they can be made more resilient. The system approach focuses as much on the context surrounding events as on the events themselves.

This principle can be visualized by the analogy of a pyramid. The clinical space, where care occurs, is at the "sharp end" of the pyramid (Figure 1.1). The clinical space is only a small part of the overall safety context.

The story presented in this chapter describes a perfusion accident that occurs in the clinical space. The immediate cause of the accident is a misapplied clamp. From a system approach, the root causes of the accident are much deeper, arising in organizational factors and team communications.

The missing term

Surgeons have traditionally been taught that patient outcomes are determined by the condition of the patient and the skill of the surgeon (surgical knowledge, technical ability, decision making, postoperative care, vigilance, etc.):

patient condition + surgical skill = patient outcome

From the system approach, the traditional outcome equation is incomplete. There is a missing term:

patient condition + surgical skill + [ ] = patient outcome

The missing term [ ] is made up of factors that most surgeons are not presently trained to recognize, consider, and manage. The missing term

accounts for the other levels of the safety pyramid: teamwork climate, trust, psychological safety, communications, leadership style, eliciting, and managing concerns and suggestions, presence or absence of distractions, attributes of the physical environment, staffing levels, policies, resource allocation decisions, patient and family engagement, and many other factors.

This shift of focus from individual to context is the fundamental contribution of safety science to clinical care. To manage risk and achieve safety at the highest levels, it is necessary to think and work at the level of context, culture, and relationships. This broader emphasis does not diminish the importance of surgical skill, but takes safety to another level by recognizing that surgical skill and other individual attributes and actions are shaped by contextual forces. It is a different way of understanding how safety is achieved, and it opens many new possibilities.

The person approach is the dominant tradition in health care. Safety science teaches that the system approach is preferable because it works better.

Two types of problem solving

Recognizing that safety has systemic roots is important but not sufficient. Achieving safety at the highest levels requires relentless curiosity about how care can be even better than it already is, combined with hardwired methods for continuously improving care at all levels. An important indication that something can be improved is when a problem surfaces. It is interesting to consider how problems are solved.

Anita Tucker of Harvard Business School has spent many hours observing work processes of health care professionals. She finds that problem solving is a major part of health care work. She divides problem solving into two types. Type I (first-order) problem solving is reactive: a problem is encountered and a solution is found that satisfies the immediate need. Type II (second-order) problem solving is deeper and more forward-looking: a problem is encountered and a new approach is devised that solves the problem now and for the future.

For example, suppose an important instrument is missing from a surgical tray. Type I problem solving would be to find the instrument and get on with the case. Type II problem solving would be to study and improve supply processes to increase the likelihood of having the instrument every time.

Type II problem solving is notably rare in health care. Of workflow problem solving observed by Tucker, 93% was type I. Another 6% was type I but included notifying someone in a way that might lead to a type II solution. Less than 1% of problem solving observed by Tucker was active type II problem solving initiated and accomplished directly by frontline staff [3].

Why is type II problem solving so rare in health care? The answer is that type II problem solving is not yet a cultural expectation in health care, and the structures, work processes, and leadership methods necessary for type II problem solving are typically missing or underutilized.

Instead, many factors maintain the status quo of type I problem solving. These include time pressure, expectations of autonomy and self-reliance, reluctance to be perceived as a complainer, and even a sense of satisfaction that comes from determinedly working around problems. More importantly, health care organizations are not well configured to support type II problem solving. Most health care work processes are "top–down directive" rather than structured to achieve frontline engagement.

There is a concept in safety science called "normalization of deviance." This means that people are so used to working around problems that they no longer recognize them as concerns. Problems are accepted as normal and type I problem solving is an everyday fact of life. Life goes on but nothing ever improves.

Safety requires type I problem solving for novel problems, but safety at the highest levels requires type II problem solving that progressively improves care at a root cause level. In other words, safety requires ongoing type II problem solving driving continuous transformation as a normal part of everyday work.

People find comfort in stable routines. In traditional health care culture, this need for stability may cause people to resist changes in care processes even when these changes might be beneficial. In an active safety culture, the need for stability is the same. What changes is the level at which stability occurs. What becomes routine and comfortable in an active safety culture is a set of stable practices that enable care teams to monitor and improve their care processes. These stable and comfortable safety practices support and enable ongoing changes in care processes at more traditional levels.

Reflective practice and organizational learning

The term "reflective practice" means taking time out from the ongoing press of work to reflect on what you are doing and how you are doing it. It is a simple concept that is essential for safety. Reflective practice is a natural part of how people work and learn. Every surgeon gives at least some thought to every case beforehand, and reflects back later about things that were particularly difficult or especially satisfying, if only to say, "I'll never do that again!" This natural tendency to think ahead and reflect back can be incorporated into daily care practices as a routine and disciplined way of working.

Consider any human activity that achieves performance at very high levels, for example, Olympic-level athletic performance. Athletes performing at the highest levels achieve excellence not only because of innate abilities, but also because of ongoing learning through meticulous preparation, detailed reflection and analysis, and continuous refinement of performance. Simply doing something well is not enough. Exceptional performance requires ongoing learning through planning, reflection, analysis, and change.

Highly performing teams require ongoing learning at the level of the team as a whole, not just by individual team members. This is because a highly

functioning team is more than the sum of its parts. The finely honed synergies and interdependencies that characterize exceptional teams do not happen without team-level learning, no matter how good the players are individually. The concept that a team can adopt new routines and learn at a level beyond the individual is called "organizational learning."

The concept of organizational learning is not familiar in health care. Instead, the focus has been on individual learning and attainment of individual performance standards. Practitioners train for a long time, demonstrate competency, then cross the finish line and enter the world of practice. Quality and safety are assumed thereafter as long as individual competency is maintained through continuing education, and benchmarks and standards are met that assure quality and safety are acceptable.

A very different paradigm of safety focuses on reflective practice, organizational learning, and type II problem solving. From this perspective, the goal is not to assure individual competence but rather to continually improve the quality and safety of care achieved through interdependent efforts of highly capable people working together in related roles. In a high reliability safety culture, safety is an evolving team and organizational attribute rather than an individual accomplishment. There is no finish line.

Achieving safety through reflective practice, organizational learning, and type II problem solving means the following: Doing something as a team or organization, observing the result, reflecting about it, and then trying new ways of doing things even better. This is the basic recipe for achieving safety at the highest levels.

Building capacity for reflective practice, organizational learning, and type II problem solving

Because most health care work involves contributions by people in multiple roles and disciplines, capacity for type II problem solving requires structures and processes that involve all of the roles and disciplines whose interdependent efforts drive outcomes. Achieving safety at the highest levels requires establishing new organizational structures and processes that cross traditional organizational boundaries and support teams and teamwork. At a minimum, this can be as simple as having weekly team meetings of people in different roles and disciplines that work together.

Ideally more comprehensive organizational resources such as staffing and scheduling processes, educational programs, measurement systems, communications structures, and information technology systems can be configured to support interdisciplinary teamwork and team learning. New resources such as simulation and evolving methods for education and certification can also be utilized in this way.

In addition, leadership methods must support reflective practice and organizational learning. This requires a facilitative kind of leadership that guides and supports the development of teams as they move toward a state of active

engagement characterized by psychological safety, curiosity, intrinsic motivation, high aspirations, mutual respect, willingness to test new ideas, and comfort with change.

Health care leaders experienced in achieving this kind of transformation are rare. Success requires deep familiarity with existing processes and an ability to think outside of existing processes in very new ways. It requires operational knowledge of organizations and clinical care, and a highly developed ability to lead transformational change not only of organizational culture but also of clinical practice culture. They are not the same.

In the experience of the authors, transforming clinical practice culture to achieve exceptional safety works best when it is motivated as an "inside-out" pull rather than an "outside-in" push. This requires redirecting organizational control to the frontline level and creating a respectful organizational culture that supports empowered frontline learning. Successful leadership of frontline learning culture must be collaborative and facilitative rather than directive and controlling.

Role-based differences in perception

One of the most interesting lessons about teamwork in health care is that people in different health care roles are likely to experience the same situation in different ways. In other words, reality as experienced by one person may not be experienced in the same way by another person, especially by those in different roles.

Sexton, Thomas, and Helmreich surveyed attitudes about teamwork of physicians and nurses working in operating rooms and intensive care units. Relative to physicians, nurses reported that it is difficult to speak up, disagreements are not appropriately resolved, more input into decision making is needed, and nurse input is not well received. In related surveys, differences in perceptions of teamwork were seen across other roles. High levels of teamwork with consultant surgeons were reported by 73% of surgical residents, 64% of consultant surgeons, 39% of anesthesia consultants, 28% of surgical nurses, 25% of anesthesia nurses, and 10% of anesthesia residents [4].

Further analysis shows that differences of perception between nurses and physicians are caused by different ideas about what good teamwork means. Nurses tend to describe good teamwork as "my contribution is valued," whereas physicians tend to describe good teamwork as "they do what I say." Nurses and physicians work from different cognitive and emotional maps of what teamwork means, and they experience reality differently even though they are working side by side [5].

The difference of perception about teamwork is one of many differences in role culture that have been documented among health care providers. Nurses, physicians, and people in other health care disciplines train in different educational tracks mostly in isolation from other roles, and they socialize

into different worldviews. Although practitioners may assume that other members of a clinical team are interpreting things in the same way they are, in fact there are often significant differences of perceptions, goals, and priorities.

The social construction of high reliability teamwork

Research suggests that highly performing teams have achieved a level of mutual understanding that transcends role differences and allows the team to work cohesively with complementary perceptions. This transition—from individuals in roles with different perceptions to a state of common ground with complementary perceptions—is likely to develop over time provided that a team interacts consistently, has opportunities for reflection and conversation, and is led in certain ways [6].

A theory of knowledge in social science known as social constructionism studies how individuals and groups participate in the creation of their own perceived realities. From a social constructionist viewpoint, how a team functions is "socially constructed" by the team through its interactions, shared experiences, and conversations [7]. The culture of a team is not static, but rather is constantly being modified as people interact and converse. For example, if people meet and talk together, they are likely to go away from the encounter a little different than they were before. Perhaps they will be more certain of something if agreement is present, or they may think about something in a new way if there are disagreements or new ideas arise during the conversation.

During traditional health care education, and also in many health care practice settings, interactions and reflective conversations among health care team members occur most frequently between people in the same role, for example, nurses talking with other nurses and doctors with other doctors. From a social constructionist perspective, these interactions and conversations occurring within a discipline are likely to create and reinforce a shared worldview unique to that discipline. However, when people in different roles are able to interact, reflect, and converse across roles, a new, blended reality begins to emerge. In other words, the same socialization processes that often maintain differences in traditional health care culture can be used to bring people together by changing the nature of their interactions.

For health care leaders interested in safety at the highest levels, social constructionism offers a lot of hope. One of the most discouraging things about the system approach to safety is that it highlights contextual factors that affect safety but often may seem beyond the control of frontline teams and leaders. Social constructionism points out that many factors that affect safety can be modified simply by providing teams opportunities to meet and talk together in new ways. Social constructionism is a new way of understanding how safety develops that is directly actionable by frontline teams and leaders.

For example, consider the challenge of trying to achieve optimum communication among health care team members. From a traditional perspective, this is a mechanistic problem, improvable by precise specification and transmission of information, better documentation, and maybe a new IT system.

From a system approach, additional factors are recognized such as time constraints, alignment of perceptions, priorities, and goals, hierarchical differences, concern with upward influence, role-related ambiguity, and conflicts of interpersonal power [8]. These are interesting and important, but at a frontline level may not seem very actionable by teams or leaders.

From a social constructionist perspective, optimum team communication is a manifestation of how teams work together, converse, and "cocreate" shared perceptions of their work and purpose in relation to one another. Effective communications and other attributes of good teamwork are outcomes of local processes that improve mutual understanding, increase common ground, create shared expectations, and align actions. These are things that teams can work on. From a social constructionist perspective, even something as simple as having weekly team meetings can make all the difference. What matters is getting people together. How a team communicates is highly tacit as well as explicit. A kind of unspoken team knowledge develops specific to a particular team and its shared history.

An important finding related to social constructionism is recognition that safety is enhanced when patients and family members participate in clinical care and decision making [9]. If care teams "cocreate" shared perceptions of their work and purpose through their ongoing interactions and conversations, patients and families should be part of these conversations. If not, patients and families will inevitably remain separate from the development of the team. The needs, goals, and potential contributions of patients and families will not be integral to the resulting team culture even though practitioner members of the team may believe the team is patient centered.

From a social constructionist perspective, optimum communications and other attributes of high reliability teamwork are likely to emerge within a team over time provided that certain preconditions are established in the local team environment. These include structures and work processes that provide opportunities for teams to interact consistently and meet regularly to talk together about their work. Also important are leadership methods that achieve engagement, mutual respect, psychological safety, and trust. Taken as a whole, these elements and attributes of the workplace environment that promote effective working relationships across roles and disciplines are known as "relational infrastructure" [10].

If the "relational infrastructure-preconditions" model of achieving high reliability teamwork is correct (our experience suggests that it is), important lessons include the following:

1 Organizational processes including resource allocation, outcome measurement, management methods, staffing, and scheduling should be designed around "natural work groups" of interdependent roles and disciplines rather than separately by individual or department.

2 Individuals in related roles should work together with enough consistency that team members can become familiar with one another.
3 Teams should have regular opportunities to interact, reflect, and converse together about their work and goals beyond time spent in direct patient care.
4 Patient and family participation should be part of all team processes.
5 Careful attention must be given to leadership methods, leadership education, and role modeling.

Evidence supporting these approaches

Pioneering studies of the influence of nontechnical factors on safety in cardiothoracic surgery include reports by de Leval, Carthey and colleagues on observations of incident sequences, errors, near misses, compensation, and error recovery during arterial switch operations [11, 12]; and Wiegmann, ElBardissi, Sundt and colleagues on organizational influences that predispose to surgical errors [13] and correlations between OR flow disruptions and surgical outcomes [14].

A variable literature exists regarding the benefits of team training in health care settings. Morey *et al*. reported a statistically significant improvement in the quality of teamwork behaviors between experimental and control groups following team training. Clinical error rates decreased and staff attitudes toward teamwork increased [15]. However, Nielsen *et al*. did not find improvements in clinical outcomes or improvement in use of appropriate process measures in a randomized controlled trial of teamwork training on obstetrics wards [16].

The concept that highly performing teams are able to tacitly coordinate their actions was studied by Gittell and colleagues who called this kind of tacit team alignment "relational coordination," defined as frequent, timely and accurate communications and problem solving, shared goals, shared knowledge, and mutual respect. In a nine-hospital study of surgical care, relational coordination measured by a cross-sectional questionnaire varied between sites and was significantly correlated with quality of care, reduction of postoperative pain, and improvement of postoperative functioning [17].

An important study with direct relevance to cardiothoracic surgery teamwork and leadership was conducted by Edmondson, Bohmer, and Pisano who studied surgical teams from 16 different institutions working to implement minimally invasive methods for open heart surgery. All of the teams were highly regarded and had excellent outcomes with traditional surgical approaches, yet there were striking differences regarding ability to successfully implement the new technology.

The factors found to be important for success were as follows:
1 Leadership actions that invited input, signaled openness to feedback, communicated a rationale for change and enhanced engagement and motivation of team members.
2 An interpersonal climate of psychological safety in which team members felt comfortable to ask questions and speak up about concerns.

3 Opportunities for reflective practice, including briefings and debriefings so that team members could more easily understand one another's capabilities and coordinate their actions.
4 Use of data for ongoing review and improvement.

Successful teams were comprised of motivated team members chosen for their interest; procedures were rehearsed and studied extensively before they were implemented clinically; leadership models were used that lowered hierarchy and encouraged open communication; teams met frequently to discuss progress and difficulties, and they were led in a collaborative rather than a directive manner. The researchers concluded that these factors increased the ability of the team to learn together and adapt.

Factors associated with failure were as follows:
1 Leadership models that did not communicate a rationale for change, did not engage or motivate team members, and that expected team members but not leaders to show up for practice sessions.
2 An interpersonal climate in which team members were discouraged from making contributions or criticized when making suggestions outside of role.
3 A lack of norms and opportunities for shared reflection.
4 Use of data for publishing or to fulfill requirements but not as an ongoing part of the implementation effort [18].

An important example of high reliability teamwork in cardiothoracic surgery is the Concord Collaborative Care Model, which received the Eisenberg Patient Safety Award in system innovation from the Joint Commission on Accreditation of Healthcare Organizations and National Quality Forum. The organization and workflows of the cardiac surgical service at Concord Hospital, Concord, New Hampshire, were reconfigured to support collaboration, high reliability teamwork, and team learning.

Changes included a weekly team meeting of all roles and disciplines caring for cardiothoracic surgical patients, daily collaborative rounds that involved all disciplines and emphasized active engagement and participation of patients and families, use of a mini-debriefing session during rounds with each patient including a "Glitch Book" in which problems encountered by the team during the course of daily care were recorded and used as a starting point for ongoing improvement of care processes, establishment of an advisory group of former patients and family members as a resource for the program, and use of leadership methods that emphasized lowered hierarchy and open communications.

Other clinical changes included improved methods of myocardial protection, simplification of care when possible including OR extubation, reduced use of lines, tubes, and invasive monitoring, reduced use of routine laboratory tests and x-rays, early activity, and "integrative clinical assessment" by team members, which is an expertise-based care model emphasizing comprehensive evaluation and early intervention.

Figure 1.2 shows the improvement of all-case cardiac surgical mortality at Concord Hospital following the institution of the Concord Collaborative Care

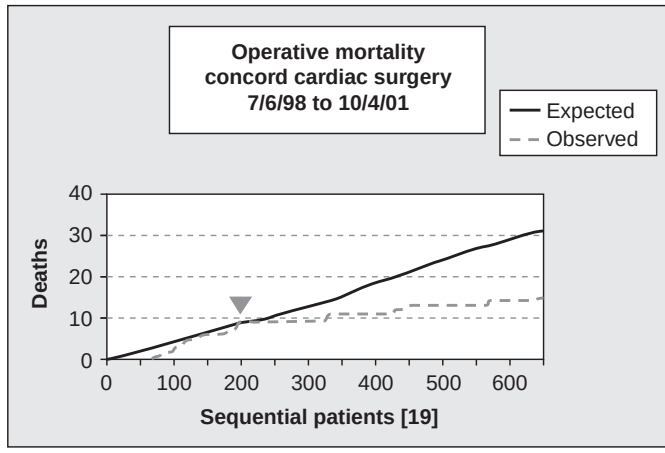

Figure 1.2 Expected and observed all-case cardiac surgical mortality, Concord Hospital [19]. Collaborative Care Model implemented at the point marked with the arrow. Expected mortality was calculated using the Northern New England Cardiovascular Disease Study Group risk prediction model electronic second opinion.

Model. Mortality and complications decreased, patient satisfaction increased to the 99th percentile, and staff satisfaction increased [19].

An interesting unpublished finding was the ability of the Concord program to make changes in traditional routines. Figure 1.3 shows a notable reduction in time to extubation after cardiac surgery at Concord Hospital compared to other hospitals in the Northern New England Cardiovascular Disease Study Group during the time the Collaborative Care Model was being developed. Similar changes were documented at Concord regarding OR use of trans-esophageal echo, and minimizing use of PA catheters (D. Galatis, Department of Anesthesia, Concord Hospital, personal communication).

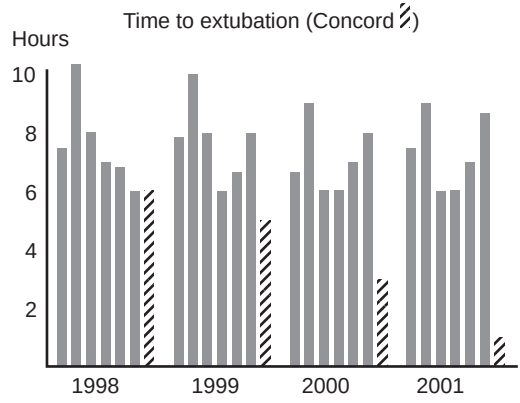

Figure 1.3 Times to extubation after cardiac surgery. (D. Galatis, Department of Anesthesia, Concord Hospital, personal communication).

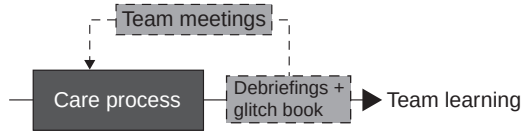

Figure 1.4 Infrastructure for team learning—collaborative care model. Debriefings and Glitch Book with weekly team meetings provides a team-based platform for improving care.

The ability to change established routines at Concord is likely related to a collaborative infrastructure that enables the team to learn together. Figure 1.4 is a representation of the way that organizational structures and workflow processes in the Collaborative Care Model facilitate team learning. Weekly team meetings and daily debriefings/Glitch recording form a team-based platform and feedback loop that enables reflective practice and ongoing improvement of care processes. These activities also allow care teams, patients, and families to improve mutual understanding, increase common ground, create shared expectations, and align actions.

An important lesson of the Concord Collaborative Care Model is that optimum care and safety can be achieved at the level of the collective team as much as at the level of the individual. The organizational structures and processes in the Collaborative Care Model are designed to support team-level cognition, evaluation, decision making, and actions. For surgeons, thinking about teamwork in this way may be hard because traditional health care practice is so focused on individual actions and decision making.

There is an extensive literature about expertise and differences between novice and expert approaches to work and decision making. Whereas novices rely on discrete steps to analyze situations and make decisions, experts use integrative pattern matching and mental simulations—the ability to recall events that happened before and to predict events that are likely to happen in the future [20]. At an individual level, cardiothoracic surgeons are familiar with these attributes of expertise and use expertise on a daily basis to provide care and make decisions. We anticipate that in the future, safety improvements in cardiothoracic surgery will result from the development of integrative expertise achieved at the level of interprofessional teams, not just as individuals.

Contemporary safety science emphasizes the importance of organizational resilience, which is the ability of systems to learn and adapt rapidly and effectively in response to novel challenges. Infrastructures and workflow processes that support team-level learning and action are essential for this capacity.

Better outcomes, hidden in plain sight

Consider the following statement: “Central line infections occur in some patients despite the most careful attention. A certain low rate of line infections is to be expected.” Consider instead another statement: “Central line infections are entirely preventable, even in the sickest patients, and should never

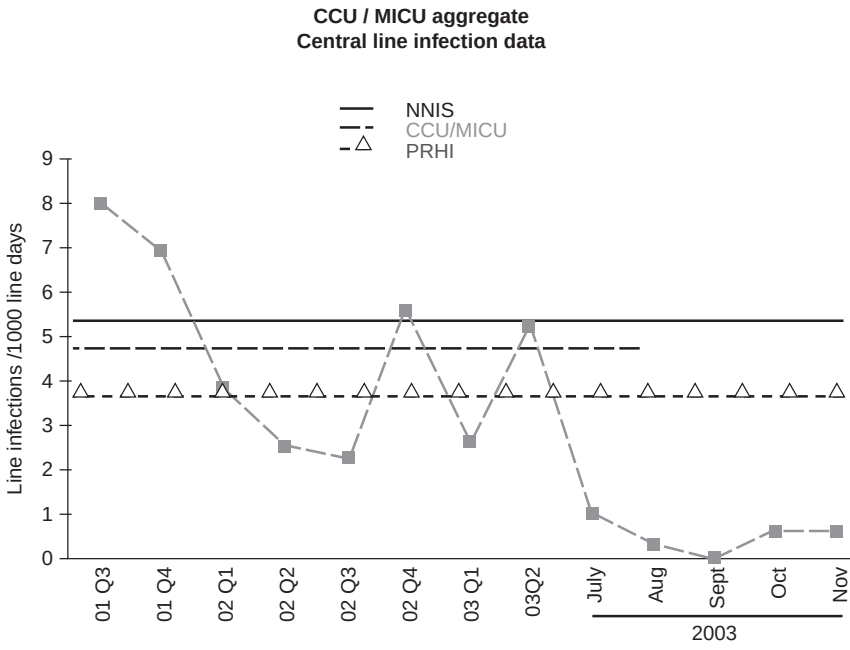

Figure 1.5 Change in central line infection rate at Allegheny General Hospital. (J. Lloyd, former Physician Advisor, Pittsburgh Regional Healthcare Initiative, personal communication).

happen." The two statements are very different. The first accepts central line infections as inevitable, and the second says just the opposite. In fact, evidence supports the second statement.

Figure 1.5 shows a change in central line infection rates in two intensive care units at Allegheny General Hospital when a set of new practices was introduced based on work standardization and a commitment to safety as a precondition of caring for patients. The number of central line infections was reduced from 49 to 3, deaths associated with central line infections decreased from 19 to 1, and the rate of infections decreased from 1 in 23 to 1 in 535 insertions [21].

Similar reductions in central line infection rates were achieved in 103 ICUs across the state of Michigan during a statewide initiative. Central line infection rates were reduced from a median of 2.7 (mean 7.7) to zero (mean 1.4) infections per 1000 catheter-days. The Michigan initiative included education of leaders and teams about safety practices, use of five evidence-based procedures for central line insertion and care, creation of a central line insertion cart in each unit, daily discussion about removal of catheters, and feedback of the number of central line infections on a monthly basis and rates of infection on a quarterly basis [22].

Opportunities for improving clinical care are often "hidden in plain sight." Who would have predicted, before these pioneering studies and others like

them, that such remarkable improvements in central line infection rates would be possible?

An important lesson is that thinking and working in systematic ways across patient populations provides additional layers of safety beyond that achieved by giving thoughtful attention to each patient one at a time. Experience suggests that applying evidence-based therapies to every patient who might benefit requires systems-based approaches, not greater individual efforts. Most practitioners know the proven value of these therapies, and believe that they are using them appropriately, yet assessments show that many patients are not receiving them. Becoming comfortable with systems-based approaches to care of populations is an important departure from traditional surgical practice.

A second lesson is that how practitioners think about clinical care can limit the ability to imagine new possibilities. What changed in the ICUs in Pennsylvania and Michigan? New methods were being used, yes. But more importantly, a belief system changed: "Central line infections can be entirely prevented." The frontiers of safety science are revealed when belief systems change.

Often, it is only our beliefs that hold us back.

Thursday morning, 7:05 a.m.

"Hi, Claire," says Marilyn, acknowledging Claire's greeting. "The cine for your first case is up on the computer, and we've got the H and P, too. They've been coming over like clockwork since Kallie from your office started coming to our team meetings." "Thanks, Marilyn," replies Claire, "Kallie likes the meetings. She says they help her get to know people and understand what we need. And she really likes the pecan rolls!" "Me too," says Marilyn. "It's hard to share a pecan roll with someone and not end up as friends."

An hour later, Claire has settled comfortably into her routine. "ACT is 300," says Dave. "300," replies Claire as she begins to cannulate. It has been 2 months since Dave has done a case with Claire, but last week they ran through several on-pump scenarios together at the 6-month simulator check. Everything felt very comfortable then, and it does now.

Dave thinks back on the last 2 months. That is how long the contract negotiations with the hospital dragged on. He sighs and shakes his head thinking about those negotiations. He looks up at Marilyn. It took a lot of courage for her to mention her concerns to him, but she was right. He had been distracted. She brought it up with him, and encouraged him to talk with the team at the weekly meeting.

Claire's voice interrupts his thoughts, "OK to clamp and cut?" Dave leans forward, turns off the arterial pump head, clamps several lines, and replies, "OK to clamp and cut." Claire watches Dave settle back into his seat. Dave—Claire thinks to herself—steady Dave who took me under his wing when I started here 4 years ago. It was just like Dave to take himself out of the perfusion rotation a month ago during the contract negotiations. There had been support from the

rest of the team when he and Marilyn brought it up at the team meeting. And it was just like him, too, to ask for a few extra simulation runs last week during the sim check. Steady Dave. A very good guy.

A few minutes later Claire has finished cannulating. She double checks the aortic line for air and looks up at Dave. "You OK for going on?" she asks. Dave nods and says, "OK for going on bypass." "On bypass please, Dave, drift to 34, keep the cardioplegia warm." Claire watches as dark red blood swirls into the venous line and drains toward the pump. She scans the field and watches the heart begin to empty.

"Marilyn, can you let the family . . ." she begins, but stops in mid sentence as her eyes move across the field to the aortic line. "Dave, is everything OK? The heart's empty but I don't see any blood yet in the aortic line, just prime."

"I know," says Dave. "I can't flow. I don't know why. It's just like our scenario last week. I can't believe it. I've clamped the venous line and I'm sorting it out. Marilyn, see if Shelly can come in and help me. Claire, I can flow to you using the cardioplegia circuit if you need more volume while I get this solved."

"No, we're OK, Dave, pressure is 70 and stable. Take your time and sort it out. Susan and I will watch for any air. John, see if you can help Dave, and watch the pressure with me, just like we did in the scenario. Susan, I need that line clamp back." Claire looks across the drapes at John, the anesthesiologist, who is now at full attention at the head of the table looking carefully at the pump and lines. "Dave," John says, "There's a clamp on the arterial line right past your main pump head. Could that be the problem?"

"No. . .Yes! I've got it John. Thanks." Claire feels a moment of relief as Dave removes the clamp and turns on the pump. "Coming up on flow now, Claire." Claire looks at the arterial line, which is flowing normally. "Venous is open, up to full flow now," says Dave. "Full flow," says Claire as she looks up at the monitor. The pressure is stable. "Incredible. Nice recovery Dave. Thanks John. Shelly, Susan, Marilyn, thank you, too." A moment later, Claire says, "Marilyn, be sure we add this to our debriefing. We should talk about this tomorrow at our meeting. When you get a minute call Dan at the sim center—this will make his day. Dave, you doing OK?" "Fine, Claire, just fine. Thanks for asking. I'm good."

In her mind's eye Claire sees Tiffany and the children sitting in the waiting room. She says to nobody in particular, "We practiced this exact scenario last week, and now it just happened! How did Dan know?" With the same thought in mind and with smiling eyes, John says, "A lot better than our first session last week, don't you think Claire?" Claire shakes her head remembering all that went wrong. "Brother, you aren't kidding! Do you remember what it was like before we started doing this stuff? I had no idea."

What do I do tomorrow?

As you read the rest of this book, think about the teamwork and safety concepts presented here. Try to imagine ways in which the complications

described in the following chapters might be entirely prevented. Extend your thinking beyond yourself and your patients to the contexts and relationships that influence your practice. Analyze your work from the perspective of type II problem solving, using the safety pyramid to guide your thinking.

Read Amy Edmundson's paper and reflect about whether your team is good at learning new routines. Consider the influence of your leadership style and whether you should lead your team differently. Develop better relationships with others you work with. Read about social constructionism. With other leaders, invite your team to begin weekly team meetings. Explain why you are having the meetings, and what you hope the meetings will accomplish. Encourage your team to read and talk about safety science. Teach your team about type II problem solving. Choose a problem and work together to resolve it. Begin to brief and debrief for every case. Establish and use a Glitch Book.

Work with your team to develop a list of high-risk critical events. Discuss the events and practice how you will manage them. Find a nearby simulation center and ask to visit. See if they will work with you to establish a simulation curriculum for your team. If there is no center, create one. At a minimum, all you need is a room and a plan. Think back about your own experiences and create scenarios from them. Try them out. Talk with colleagues interested in these ideas. Invite others to participate with you. Attend a simulation conference or training program. Learn from an expert facilitator how to debrief the sessions.

Carry these ideas into the ICU. Start weekly team meetings including nursing, pharmacy, RT, PT, social work, and the unit secretary. Develop and use checklists and daily goals sheets for each patient. Work with your hospital IT and quality departments to develop a one page "data map" of key indicators you and your team can follow and work together to improve on a real-time basis. Develop a collaborative rounds process that actively includes patients and families in care and clinical decision making. Establish a patient–family advisory council and utilize their experiences and expertise to improve your unit.

Begin to imagine 100%/zero goals—100% patient satisfaction, 100% professional satisfaction, zero line infections, zero complications, and zero deaths. Challenge your team: How can we achieve these? Become a role model for your colleagues. Develop a grand rounds presentation about safety science for your hospital. Collect data, give presentations, and publish the experiences and results of your team.

Meet, reflect, and imagine. Test, teach, and lead. And most importantly, be open to change. As you do these things, invite others to rewrite their story with you. You will be fascinated by what is possible.

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CHAPTER 2

Thoracic Incisions

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Introduction

Thoracic surgical history dates to ancient times with the management of empyema. Hippocrates described rib resection and pleural drainage 2400 years ago [1]. Five centuries later, Galen noted that entering the pleural space resulted in arrest of ventilation and circulation [2]. Recognition of this dire complication limited operative intervention in the chest. Surgery in the pleural cavity was thus prohibited by the problem of ventilation and the problem of open pneumothorax. During the subsequent two millennia, no significant advances in thoracic surgery transpired. Safe and effective surgery in the chest, as with all other operations, required knowledge of potential complications and strategies to prevent their occurrence.

Vesalius was among the first to utilize endotracheal intubation in animal studies, via a tracheostomy, keeping the animal alive by insufflation [3]. In the latter eighteenth century, Curry developed endotracheal intubation for resuscitation of drowning victims, and in 1807, Chaussier designed a cannula for laryngeal intubation and lung inflation in order to revive newborns. Later in the nineteenth century, MacEwen reintroduced tracheal intubation and lung inflation to achieve continuous anesthetic delivery. In 1887, Fell introduced an apparatus to maintain artificial respiration via a face mask or tracheostomy and subsequently O'Dwyer substituted a tracheal tube and introduced bellows operated by foot. Matas reported resection of a large chest wall sarcoma using the Fell–O'Dwyer apparatus in 1899. Thereafter, endotracheal intubation became the standard modality for artificial respiration and anesthetic delivery.

With the development of positive pressure ventilation and anesthetic insufflation, intrapleural surgery became possible. Differential lung ventilation was made possible by the introduction of the double lumen endotracheal tube, introduced in 1940 by Zavod [4] and advanced by Carlens in 1949 [5] allowing isolation of the diseased lung and selective controlled ventilation in open thoracic procedures.

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With the ability to safely operate in the chest, optimizing operative exposure became paramount. Indeed, the evolution of thoracic incisions paralleled advances in thoracic surgery. Thoracic anatomy provided distinct challenges when designing incisions. Specifically, the rigid chest wall, large intrathoracic volume, separate pleural cavities, and diverse pathologic processes required development of a variety of incisions. For pulmonary procedures, access to the hilum is critical, while anterior approaches are ideal for cardiac and other mediastinal operations. Initially, wide exposure was considered the dominant principle. Advances in thoracic techniques allowed increasing emphasis on muscle- and rib-sparing strategies. More recently, minimally invasive approaches utilizing video-assisted thoracoscopic surgery (VATS) and robotic surgery have provided a larger selection of incisional options.

Certain guiding principles influence the choice of the optimal thoracic incision for a specific procedure. The incision must provide adequate exposure to safely accomplish the goals of the operation. In particular, the area of greatest expected operative difficulty should be sufficiently exposed. Yet the incision should be designed to preserve chest wall function and appearance. For example, muscle sparing and rib preservation may improve postoperative recovery. Incisional strategies to minimize pain, such as avoidance of excessive rib or sternal spreading, as well as injury to neurovascular bundles, should also be considered. And widely accepted surgical principles such as skin incision placement along Langer's lines, gentle handling of tissues, pinpoint hemostasis, and strict layered closure will diminish the risk of wound complications. This chapter will highlight preoperative planning, operative strategies, and postoperative care designed to minimize the occurrence of complications related to thoracic incisions.

Thoracotomy incisions

Posterolateral thoracotomy

Posterolateral thoracotomy is the standard incision for a host of intrathoracic procedures, including pulmonary surgery, esophageal operations, aortic reconstruction, and mediastinal surgery. The major advantage is the wide range of thoracic exposure. However, it carries noteworthy disadvantages: when the incorrect intercostal space is selected, exposure can be compromised; early, as well as chronic, postoperative pain related to rib spreading is a significant disability; division of chest wall muscles results in diminished respiratory and shoulder function; single lung ventilation is typically essential; and the scar is cosmetically unappealing.

Proper positioning of the patient in the lateral decubitus position is critical to preventing certain complications [6, 7]. The operating table flex point is located above the iliac crest, below the costal margin. All pressure points, including the lateral malleolus, knee, hip, and elbow are padded to avoid pressure necrosis. The lower leg is flexed at the hip and knee while the upper leg is kept straight, with pillows in between. An axillary roll may decrease

the risk of brachial plexus injury. It may also elevate the thorax off the table and permit better respiratory excursion of the dependent lung. The arms are extended, but shoulder hyperextension greater than 90° is avoided to prevent brachial plexus neuropathy. The upper arm is supported with pillows or a padded armrest, ensuring that both ulnar nerves are protected from pressure damage. The operating table is flexed to widen the intercostal spaces on the operated side. This simple maneuver may decrease excessive rib retraction and postoperative pain. Either soft rolls or a beanbag is used to secure the patient on the table. The beanbag is quite rigid and may expose pressure points to increase the risk of ischemia. The neck is maintained in a neutral position.

The incisional technique directly influences the risk of postoperative complications. Landmarks for the skin incision are the inframammary crease at the anterior or midaxillary line, a point 2–3 cm below the scapular tip, and a point midway between the spine and the medial border of the scapula. The incision is formed as a crescent or gentle S shape. It is designed to allow elevation of the scapula, exposing the proper intercostal space. Meticulous hemostasis is paramount, especially since the incision divides large muscles. Electrocautery use is appropriate, but the surgeon must avoid excess use with resultant necrotic tissue and increased risk of wound infection. Blood vessels may retract into the muscle and bleed later, so they should be cauterized in a methodical and precise manner. After dissecting through the subcutaneous tissue, the latissimus dorsi is divided. While the serratus anterior can be divided, it is usually unnecessary as it can be easily preserved by mobilizing and retracting it anteriorly. After the auscultatory triangle is opened posteriorly, the trapezius and rhomboid muscles may be partially divided as needed for scapular elevation. A scapular retractor can be inserted to facilitate counting the ribs. The surgeon's hand is advanced along the erector spinae muscle to palpate the first rib posteriorly. It is recognized by its broad flat horizontal upper surface. By counting down from the first rib, the appropriate interspace can be identified. For most pulmonary resections, the fifth interspace is chosen.

The pleura may be entered using a variety of techniques including via the intercostal space, as well as through the bed of a rib (Figure 2.1) [7]. Electrocautery is used to incise the intercostal muscles along the superior aspect of the rib. The lower margin of the rib is never used in order to avoid injury to the intercostal neurovascular bundle. Posteriorly, it is critical to dissect on the upper rib edge to avoid injury to the intercostal neurovascular bundle that is located in the center of the interspace in this area [8]. Intercostal neuralgia from nerve damage, as well as postoperative hemorrhage from undetected vascular injury, should thus be minimized [9]. The intercostal muscles can be incised, from within the pleural space, further anteriorly and posteriorly than the ends of the incision, allowing wider separation of the ribs without rib fracture. The intercostal muscle division can be taken to the internal mammary vessels in the anterior direction while the posterior dissection can be

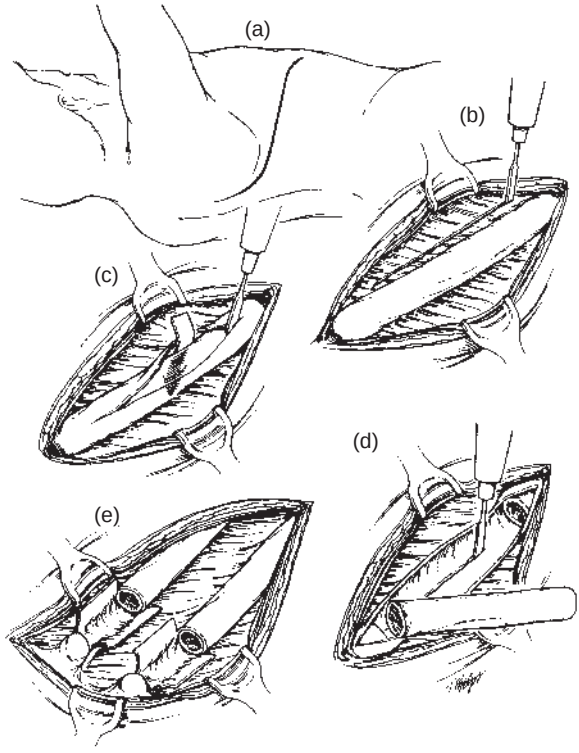

Figure 2.1 Options for entering the pleural cavity. (a) S-shaped incision. (b) Division of the intercostal muscles from the superior edge of the rib. (c) Reflecting the periosteum from the superior edge and entering though the periosteal bed. (d) Subperiosteal rib resection. (e) Intercostal approach with short segment posterior rib resection. (*Source*: From Ref. [7]; reprinted by permission. Courtesy of The McGraw-Hill Companies)

carried to the costotransverse process articulation preserving the sympathetic chain. The rib spreader is then inserted and slowly opened, lessening the risk of fracture. An alternative approach is to utilize an intercostal incision, but to divide one or more ribs by resecting a short segment posteriorly, thus allowing wider rib separation. Another method is to reset a rib and enter the pleural space through the periosteal bed. Rib resection is not required for routine thoracotomy. But, it is advantageous in cases when a rib graft is required or when significant intrapleural fibrosis or adhesions limit entry into the chest, as with reoperative surgery or in complicated decortication. However, it is time consuming to open and close; increases the likelihood of intercostal neuralgia; increases postoperative pain and thus the risk of respiratory complications; and in children causes developmental chest wall abnormalities [10, 11].

Layered closure of a posterolateral thoracotomy, as with all thoracic incisions, requires the same degree of meticulous attention to detail as all other steps of the procedure. Restoration of chest wall integrity and strength

minimizes postoperative respiratory dysfunction and pain. The technique of chest wall closure depends on whether a rib is resected. If so, then wide pericostal sutures are placed around the remaining superior and inferior ribs. Alternatively, interrupted sutures can be utilized to approximate the opposing intercostal muscles [7]. More commonly, an intercostal space approach has been used. Heavy absorbable pericostal sutures are placed around the ribs in a manner avoiding injury to the intercostal neurovascular bundle. Superiorly, the suture is passed close to the rib margin. Inferiorly, it may be beneficial to exclude the neurovascular bundle from encirclement by passing the sutures between the inferior margin of the rib and the bundle [8]. Cerfolio and colleagues [12] demonstrated diminished postoperative pain using an intracostal suturing technique. Heavy sutures are placed through drill holes in the lower rib and over the superior margin of the upper rib. If ribs have been fractured, two options are reasonable in order to eliminate painful motion of the fractured ends: a short segment of rib can be resected preventing the fractured ends from contact; or, a figure of eight pericostal suture can be placed spanning the fracture to immobilize it. The chest wall is then closed in anatomic layers to promote healing, strengthen the incision, and prevent leakage of fluid and air. The latissimus dorsi is ideally closed in two layers, separately reapproximating the anterior and posterior fascia, to minimize muscular bunching that results in a cosmetically unappealing ridge at the incision.

The most bothersome complication of thoracotomy is postoperative pain. Its reported incidence varies widely, from 5% to 80%, depending on its definition [13–15]. A reasonable estimate is that it affects more than 50% of patients after thoracotomy. Division of the skin, soft tissue, and muscle, as well as intrapleural irritation, may contribute to discomfort. However, the primary cause of postthoracotomy pain is rib spreading with resultant injury to rib articulation joints, ligamentous strain, rib fractures, and intercostal nerve damage. Muscle-sparing techniques may reduce postoperative pain. Similarly, techniques that limit rib retraction may be beneficial. Minimally invasive surgery, namely VATS, eliminates rib spreading and thus results in diminished postoperative pain [16]. Predictors of postthoracotomy pain include pain intensity 24 hours after surgery, early postoperative analgesic consumption, female gender, preoperative narcotic use, chest wall resection, pleurectomy, and postoperative radiation therapy [13]. Since there appears to be a relationship between early postoperative pain, as well as greater analgesic usage, and postthoracotomy pain syndrome, it has been suggested that aggressive and effective early analgesia may diminish the rate of longer term pain syndromes. A multimodality approach consisting of a regional anesthetic technique, such as thoracic epidural anesthesia, initiated prior to thoracotomy and continued into the postoperative period, in conjunction with a systemic opioid and a nonsteroidal anti-inflammatory drug (NSAID), might be more effective than single modality approaches [13, 15]. Alternative regional anesthetic techniques include intercostal nerve block, continuous

extrapleural nerve blockade, and intrapleural analgesia [7, 17]. Continuous catheter infusion of local anesthetic into the incision using an elastomeric pump can reduce postoperative pain [18]. Additionally, placement of the catheter in the extrapleural plane, tunneled in the paravertebral space from inferiorly to superiorly, can provide multilevel intercostal nerve blockade [19]. A preemptive analgesic strategy prevents not only postoperative discomfort but also peripheral and central nerve sensitization in an attempt to lower the incidence of chronic pain [14, 15]. Initiation of thoracic epidural anesthesia prior to thoracotomy is a rational preemptive approach. Additionally, Cerfolio and associates [20] used a preemptive analgesic strategy of intercostal muscle flap mobilization prior to rib spreader insertion to avoid injury to the intercostal nerve. While a variety of approaches to minimize postthoracotomy pain are reasonable, it is clear that the "balanced analgesia" approach utilizing multimodal methods results in superior pain control with better patient satisfaction and diminished postoperative complications resulting from limited ambulation and respiratory compromise [15].

Another complication of thoracotomy is postoperative shoulder dysfunction [6]. The disabling effect of thoracic surgery on shoulder function is underappreciated and rarely studied. Disability in shoulder function occurs in 10–26% of patients in the first year after thoracic surgery. Proper positioning of the patient includes avoiding shoulder hyperextension and excess abduction, as well as pressure injury to the contralateral brachial plexus. The muscles potentially divided during thoracotomy, including the latissimus dorsi, serratus anterior, and trapezius, directly impact shoulder function. Thus, preservation of chest wall muscles through muscle-preserving techniques or minimally invasive surgery may preserve postoperative shoulder range of motion. Also, avoiding injury to the nerves that innervate the muscles, including the long thoracic and thoracodorsal nerves, should conserve postoperative shoulder function.

Postoperative chest wall hernias can occur as a result of inadequate closure in combination with situations that increase intrathoracic pressure such as coughing or heavy lifting [21]. Predisposing factors include chronic obstructive pulmonary disease, tissue weakness or poor healing resulting from malnutrition, chronic steroid use, or diabetes, and elevated intrathoracic pressure secondary to morbid obesity. Prevention of chest wall hernia is achieved by meticulous layered closure, avoidance of wound infection, and optimization of the patient's immune and nutritional status before and after surgery. Small asymptomatic hernia defects can be observed. However, evidence of impending incarceration, such as increasing size, pain, and difficulty reducing the hernia, mandates repair. After reduction of the lung and resection of the hernia sac, the chest wall defect can be closed in a variety of manners, including polypropylene mesh, PTFE patch, wires with muscle reapproximation, or pericostal fixation with sutures bringing the adjacent ribs together. Soft tissue coverage with muscle or omental flaps is occasionally required.

Muscle-sparing thoracotomy

Posterolateral thoracotomy results in significant postoperative pain and shoulder dysfunction. Early observations that sparing the large shoulder girdle muscles results in diminished pain and morbidity encouraged the development of muscle-sparing incisions for intrathoracic access [22–24]. Much of the benefit of muscle-sparing thoracotomy has been overshadowed by the advances in VATS. Nevertheless, muscle-sparing options are excellent alternatives to posterolateral thoracotomy when VATS is not feasible. The various muscle-sparing incisions differ in their location on the thorax and in which muscles are spared and divided. Anterior incisions may divide or reflect the pectoralis major while anterolateral thoracotomy involves reflection of the latissimus dorsi posteriorly and division of the serratus anterior in the direction of its fibers (Figure 2.2). The incision on the serratus must be placed

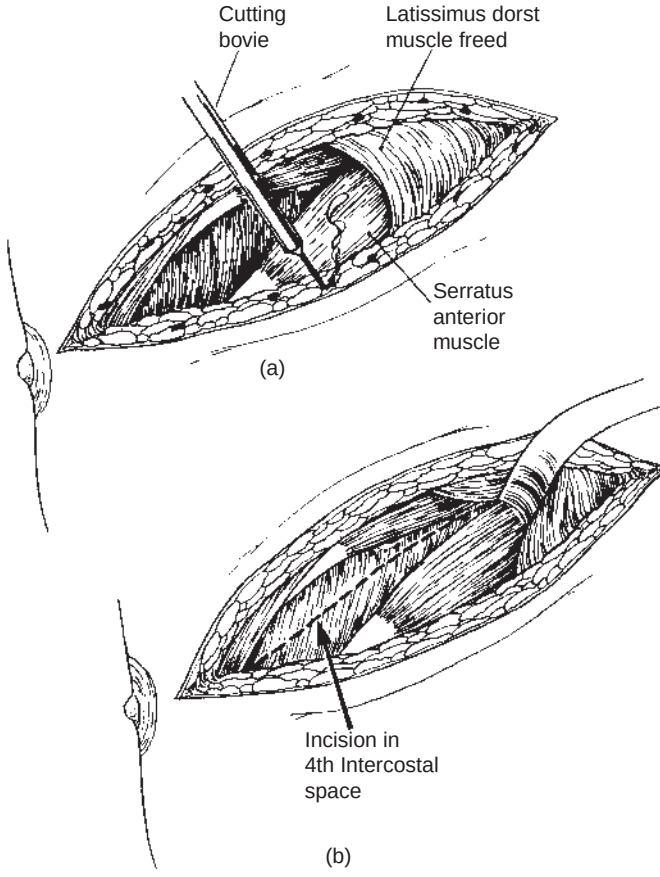

Figure 2.2 Anterior muscle-sparing thoracotomy. (a) Mobilization of the latissimus dorsi to allow retraction rather than division. (b) Division of the serratus anterior in the direction of its fibers. (*Source*: From Ref. [25]; reprinted by permission. Courtesy of Mosby, Inc.)

anterior to the long thoracic nerve. The muscle can then be mobilized while preserving its innervation, preventing winging of the scapula, a very debilitating complication. Alternatively, the serratus may be separated at its anterior rib attachments. In general, muscle-sparing thoracotomies require creation of subcutaneous flaps to permit the mobility required for retraction of the muscles in order to gain sufficient exposure. Once the appropriate interspace is identified, the chest wall is opened as with a standard thoracotomy. Frequently, two rib retractors placed in a perpendicular manner are used to optimize exposure by spreading the ribs with one and the muscles with the other.

An additional muscle-sparing thoracotomy is the posterior or auscultatory triangle incision. Here the latissimus dorsi is retracted anteriorly and the serratus anterior upward (Figure 2.3). The dissection of the subcutaneous flaps may predispose to seroma formation [25]. Fixing the latissimus dorsi to the underlying fascial layer may diminish seroma formation. Most seromas require no intervention and resolve spontaneously; however, aspiration is appropriate for treatment and for assurance that they are not infected. Some authors recommend routine closed suction drainage of the subcutaneous space to minimize seroma formation.

The vertical axillary thoracotomy is another muscle-sparing variant [26]. The length of the incision can be varied depending on the degree of exposure required. If extended, sufficient exposure is obtained to permit major pulmonary resection. The latissimus dorsi is mobilized and retracted laterally while the serratus is either split in the direction of its fibers or detached from the ribs anteriorly. The long thoracic nerve is carefully preserved, particularly where it runs close to the anterior border of the scapula at the level of the higher intercostal spaces [27]. Placement of certain axillary incisions must be planned in order to avoid nerve injury and winging of the scapula (Figure 2.4). This occurs from loss of serratus muscle tension that normally pulls the scapula downward and anteriorly, thus allowing the counteracting muscles to dominate. This results in outward and upward scapular rotation. When dividing the serratus, it is essential to do so as low as possible. Division inferior to the scapular tip assures sufficient innervation and functional muscle to maintain scapular support. Winging of the scapula, as well as diminished range of motion and pain in the shoulder, causes significant patient disability and distress.

It is generally accepted that muscle sparing results in less postoperative pain and improved postoperative respiratory function and mobility. Yet this has been difficult to conclusively demonstrate [28–30]. Lemmer and colleagues [28] demonstrated less early postoperative reduction in FEV_1 and FVC when employing a muscle-sparing approach compared to standard thoracotomy, but no differences in length of stay, opioid use, complications, or seroma formation. Ponn and associates [30] compared late pulmonary function after muscle-sparing and posterolateral thoracotomy, concluding that certain spirometric measurements were slightly different, but of no apparent clinical

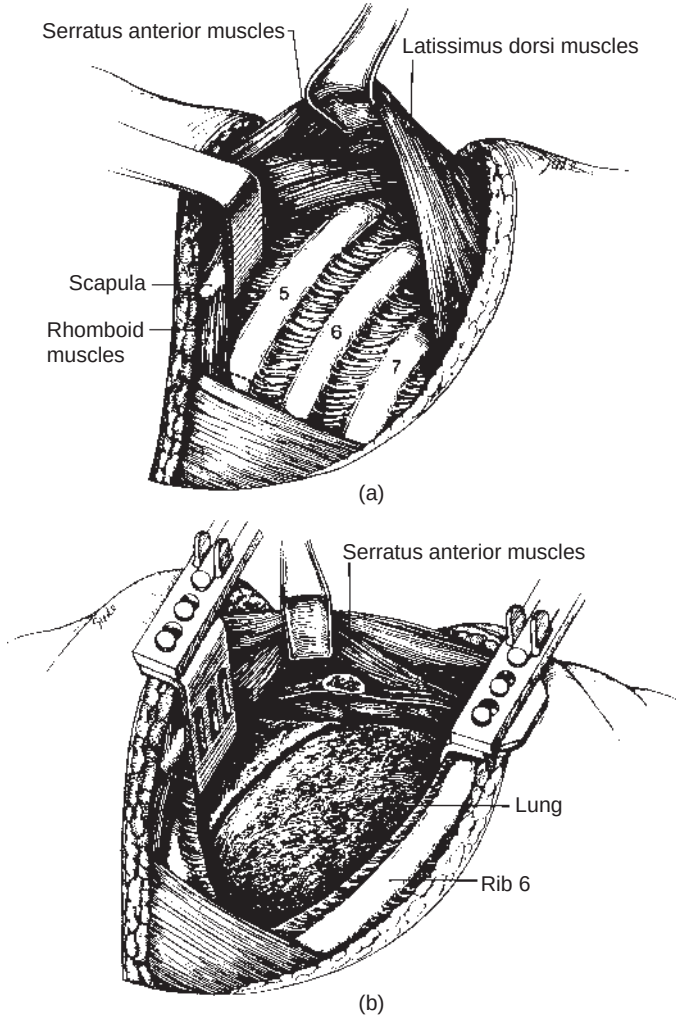

Figure 2.3 Posterior muscle-sparing thoracotomy. (a) The lattisimus dorsi and serratus anterior muscles are mobilized. (b) Generous exposure is provided through the auscultatory triangle. (*Source*: From Ref. [23]; reprinted by permission. Courtesy of Elsevier Science, Inc.)

significance. Hazelrigg *et al*. [31] prospectively randomized patients to muscle-sparing or standard posterolateral thoracotomy and demonstrated less postoperative pain, less narcotic use in the first 24 hours, lower visual analog scales for the first week, and increased shoulder girdle strength at 1 week postoperatively in the muscle-sparing cohort. Nevertheless, there was no difference in pulmonary function, shoulder range of motion, length of stay, morbidity, or mortality. Longer term studies have shown little difference in postoperative pain syndrome incidence, suggesting that factors other

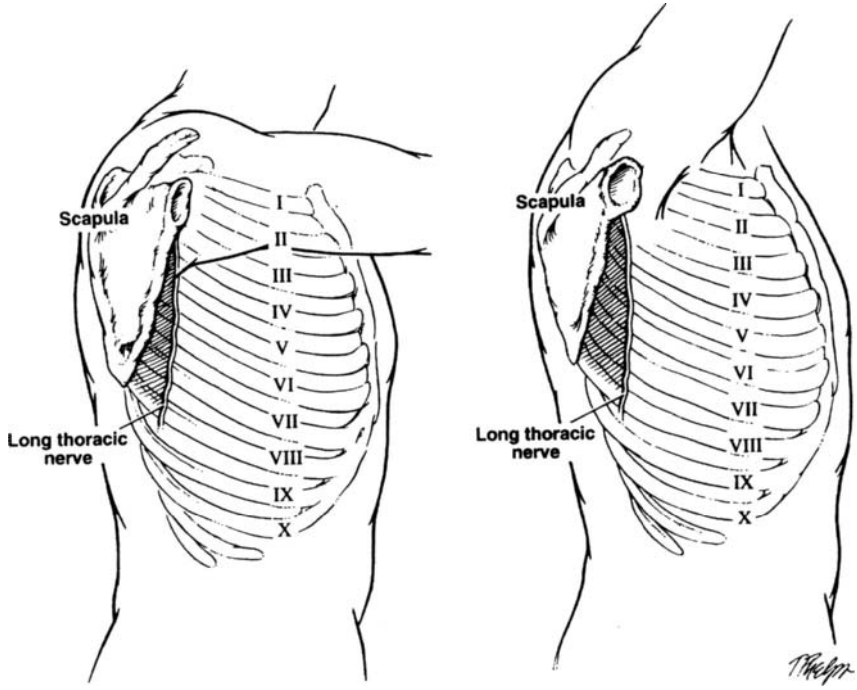

Figure 2.4 Proximity of the long thoracic nerve to the anterior scapular border. Incisions should avoid the nerve, including muscle-sparing axillary thoracotomy and VATS. (*Source*: From Ref. [27]; reprinted by permission. Courtesy of Mosby, Inc.)

than muscle division contribute to postthoracotomy pain. As noted above, rib spreading, intercostal nerve injury by retractors and during chest wall closure, and inadequate preemptive and early postoperative pain control are critically important factors [13, 14]. While some of the perceived benefits of muscle sparing have not been conclusively demonstrated, it is undeniable that the techniques are valuable for preservation of large muscle groups for use as flaps in patients requiring tissue transfer to protect suture or staple lines or fill infected cavities [32].

Thoracoabdominal incision

The left thoracoabdominal incision is indicated for certain operations involving the distal esophagus, stomach, spleen, left hemidiaphragm, and aorta [33]. Its primary advantage is superb exposure of the upper abdomen and lower hemithorax. It permits single incision exposure of the thoracoabdominal aorta and maximizes resection and reconstruction options for tumors near the gastroesophageal junction. The potential disadvantages of the incision are incisional pain, costal margin instability, diaphragmatic hernia, and hemidiaphragmatic dysfunction. Nonetheless, the incision is remarkably well tolerated.

The patient is placed in the right-lateral decubitus position with the hips rotated back to 45°, permitting increased abdominal exposure. The incision follows a straight line from just below the scapular tip to a point midway between the xiphoid and umbilicus. The latissimus dorsi and serratus anterior muscles are divided. The chest is typically entered via the seventh intercostal space. The costal margin is divided and a short segment is removed to prevent overlap of the cut edges, and resulting pain, after closure. The abdominal wall is opened in layers. In order to prevent phrenic nerve injury, the hemidiaphragm is opened circumferentially, leaving a rim of muscle with which to close later. Alternatively, the hemidiaphragm can be opened radially toward the esophageal hiatus.

The thoracoabdominal incision is closed by first reconstructing the hemidiaphragm with interrupted nonabsorbable sutures. The ribs are reapproximated with heavy pericostal sutures. The costal margin is closed with a single absorbable figure of eight absorbable suture that also incorporates the diaphragm to prevent a hernia. Overlap of the cut costal edges is avoided to prevent postoperative pain.

Another complication of the thoracoabdominal incision is infection at the costal closure. It may present with erythema, fluctuance, or a purulent draining sinus. Since the cartilage derives its blood supply from the perichondrium, surgical disruption may render the segment ischemic and susceptible to infection. In order to avoid necrosis, the costal margin should be divided sharply rather than with electrocautery. Superficial infections can be managed with local drainage and wound care. However, deep infections should be widely drained and the cartilage excised. It is controversial whether the entire costal arch should be resected. If limited debridement of sinus tracts is unsuccessful in eradicating infection, then wide excision, with or without muscle flap coverage, is indicated. Prevention of this complication is achieved with appropriate administration of perioperative antibiotics, as well as secure closure of the costal margin with absorbable suture, thus eliminating the material as a nidus for infection.

Bilateral thoracosternotomy (clamshell incision)

Early cardiac surgery was frequently performed via bilateral thoracosternotomy or clamshell incision. Increased use of the median sternotomy relegated its use to rare situations. However, new indications have evolved and it is again a standard incision, now used for bilateral pulmonary transplantation, resection of large anterior mediastinal tumors with lateral intrapleural extension, and bilateral pulmonary metastasectomy [7, 8, 34, 35]. Conversion of an emergency anterior thoracotomy into a clamshell incision provides wide exposure of the heart, mediastinum, and bilateral pleural cavities [8]. The patient is placed in the supine position. A double lumen endotracheal tube should be utilized. The arms are padded and placed on arm boards or flexed 90° and secured to a stand or the ether screen. The skin incision is placed in the inframammary crease and follows the interspace to the anterior axillary line

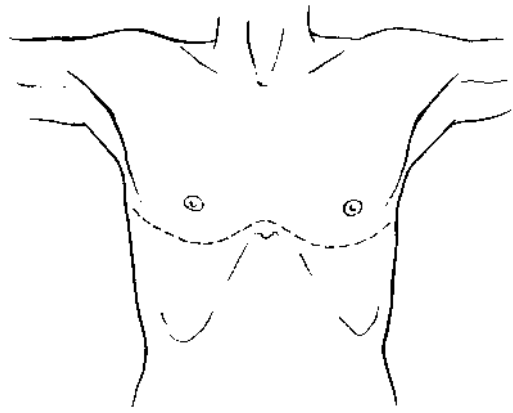

Figure 2.5 Placement of the skin incision for the bilateral thoracosternotomy (clamshell approach). The inframammary incisions follow the interspaces. (*Source*: From Ref. [35]; reprinted by permission. Courtesy of Elsevier Science, Inc.)

(Figure 2.5). The internal mammary vessels require ligation and division. The intercostal incisions are made at the fourth or fifth interspace. The sternum is divided with an oscillating or Gigli saw, or Lebsche knife and rib spreaders are placed bilaterally.

Closure is achieved with pericostal sutures bilaterally and two vertically placed sternal wires. Two short segments of Kirschner wires can be inserted in the marrow cavity, crossing the sternotomy, preventing postoperative overriding of the sternal edges. Layered closure of the chest wall follows the technique used for thoracotomy.

Cervicothoracic incisions

Occasionally, simultaneous exposure of the lower neck and thorax is required. Indications for cervicothoracic incisions include anteriorly located superior sulcus tumors, approached via an L-shaped transclavicular incision; trauma to the great vessels in the mediastinum or lower neck, approached via a hemiclamshell or trapdoor incision; and pathology of the trachea, anterior mediastinum, or proximal esophagus, approached by a T-shaped cervical collar incision and upper partial sternotomy (discussed later).

An anterior approach, with or without posterolateral thoracotomy, permits resection of anterior superior sulcus tumors adjacent to the subclavian vessels [36, 37]. With this exposure, tumor invasion of the vessels can be evaluated. When necessary, the vessels can be resected and reconstructed. The patient is placed in the supine position with the head rotated away from the involved side. An L-shaped incision is created along the anterior border of the sternocleidomastoid muscle and then extended laterally, inferior to the clavicle. The attachments of the sternocleidomastoid are dissected off the sternum and clavicle, and the upper attachments of the pectoralis to the clavicle are

dissected. The omohyoid muscle is divided and the scalene fat pad is examined for metastases. The thoracic inlet is inspected by opening the intercostal space below the tumor, and if the tumor is resectable, the medial half of the clavicle is resected. On the left side, the thoracic duct is ligated to prevent chyle leak. The subclavian vessels are dissected and examined. If invasion of the vein is detected, it can be resected. Arterial invasion requires resection and reconstruction. Chest wall resection is then performed, followed by pulmonary resection. Upon completion of the resection, the cervical incision is closed in layers. The sternal insertion of the sternocleidomastoid is sutured. Several authors have expressed concern about the functional effects of medial clavicular resection. An alternative approach is to perform an oblique osteotomy through the wide portion of the clavicular head. The clavicle is then retracted out of the operative field while performing the lobectomy and en bloc chest wall resection. The chest wall is then reconstructed, if needed, and the clavicle is rewired. An arm sling is used for 4–6 weeks postoperatively. Wound healing problems are a risk when the primary subclavian arterial branches and internal and external mammary arteries are sacrificed, particularly after neoadjuvant therapy. Wound dehiscence can extend deeply and aggressive surgical debridement followed by vacuum-assisted closure can reverse the complication [38].

The hemi-clamshell incision allows visualization of the ipsilateral mediastinum and apical hemithorax. It combines an anterior thoracotomy in the fourth or fifth intercostal space, carried halfway across the sternum, with a partial vertical midline sternotomy carried to the suprasternal notch (Figure 2.6). The ipsilateral internal mammary vessels are ligated and divided. Upward extension of the incision provides exposure of the lower neck. Closure is achieved with reapproximation of the sternum with wires and ribs with pericostal sutures.

The trapdoor incision combines an anterior thoracotomy and partial sternotomy with a supraclavicular incision. The origin of the sternocleidomastoid muscle is divided and the middle of the clavicle is resected in a subperiosteal manner. The ipsilateral internal mammary vessels are ligated and divided. Despite the complex nature of the hemi-clamshell and trapdoor incisions, they appear well tolerated and few complications are reported. Musculoskeletal and somatic complaints seem comparable to those with standard thoracotomy [39].

Mediastinoscopy and mediastinotomy

Surgical exploration of the mediastinum remains an invaluable tool in the diagnostic armamentarium of the thoracic surgeon. Although advances in imaging modalities and endoscopic techniques have lessened the indications for surgical mediastinal sampling, it continues to be useful for the diagnosis and staging of thoracic malignancies, as well as the diagnosis of benign mediastinal pathology. Early reports of nodal sampling to determine surgical resectability of lung cancer described unilateral cervicothoracic exploration.

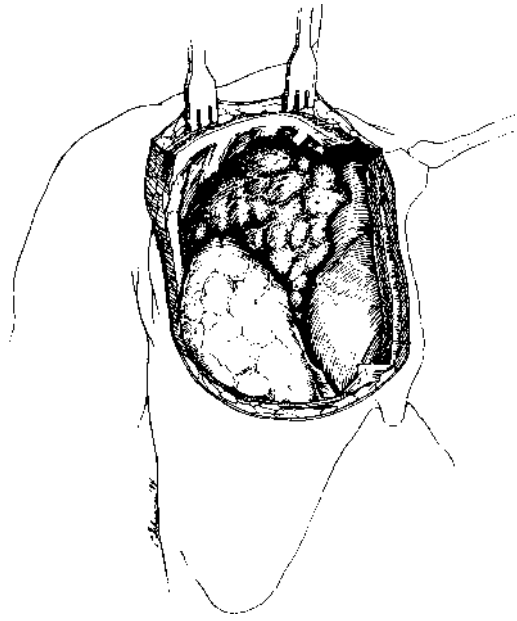

Figure 2.6 Exposure of a superior mediastinal tumor via a right hemi-clamshell incision. (*Source*: From Ref. [35]; reprinted by permission. Courtesy of Elsevier Science, Inc.)

Carlens [40] described midline cervical mediastinoscopy in 1959. The current technique is essentially unchanged. A host of vital structures are present in the superior mediastinum, and thorough knowledge of their anatomic relationships is critical to avoid intraoperative injuries, some of which can be catastrophic. The patient is positioned supine with a roll behind the scapulae maximally extending the neck, while assuring that the weight of the head is resting on the bed, rather than "floating." Inadequate neck extension makes visualization challenging. A transverse incision is made just above the suprasternal notch. The platysma is divided and the avascular pretracheal plane is entered. Initially, gentle digital dissection permits exploration at the thoracic inlet and provides a space to insert the mediastinoscope. Surgical mishaps are minimized by constant awareness of the relationship of anatomic structures to the airway, which serves as a consistent landmark. Teaching the operation can be greatly facilitated by using a video mediastinoscope. A variety of injuries to intrathoracic structures have been reported. However, the complication rate is 3% with less than 1% mortality. The surgical incision is rarely a cause of complications. Wound infection occurs in 0.10–0.15%. As with complex thoracic incisions, mediastinoscopy incisional complications can be minimized by meticulous layered closure. The strap muscles can be reapproximated at midline with interrupted sutures to minimize hematoma in the subcutaneous tissues. The platysma can be closed with a running absorbable suture while the skin is closed with a subcuticular suture. When wound infection occurs,

open drainage of the skin and subcutaneous tissue will likely suffice. Mediastinal drainage is rarely indicated. A perceived risk of the procedure, tumor seeding is also quite rare, with an incidence of 0.12%. There is no clear way to lower the risk. If it occurs, radiation therapy may provide local control.

Anterior mediastinotomy was described by McNeill and Chamberlain in 1966, and its indications remain the same: biopsy of nodes or masses in the superior mediastinum, the anterior and superior hilum, and the upper anterior portions of the lung. The advantage of the incision is its straightforward access to the aforementioned regions. Its disadvantages include the inability to access the posterior hilar region, the potential need to ligate the internal mammary vessels, and wound healing problems resulting from limited anterior soft tissue coverage. A 6 cm transverse incision is made over the second or third costal cartilage. The pectoralis muscle is divided in the direction of its fibers, exposing the entire costal cartilage that is then excised subperichondrially. The internal mammary vessels may be ligated and divided. The pleura is reflected laterally and the mediastinum is entered. Alternatively, an intercostal incision in created, preserving the costal cartilage. The pleural space can be opened for exposure. Additionally, a mediastinoscope can be inserted for improved visualization. At closure, a catheter is inserted in the pleural space and withdrawn under suction during a Valsalva maneuver. The wound is closed in layers. Complications of the Chamberlain procedure are rare, most of which are unrelated to the incision.

VATS

Thoracoscopy has been used for endoscopic exploration of the thorax since the middle of the nineteenth century [41]. Advances in video technology permitted expanded use in the 1980s. The use and indications for VATS have broadened considerably in the past 20 years. VATS has been routinely utilized for minor pleural procedures such as pleural biopsy, drainage of effusions or hemothoraces, pleurodesis, and limited pulmonary procedures including bullectomy and wedge resection. Its application to major thoracic procedures subsequently emerged and VATS is used for a host of operations including the following: anatomic pulmonary resections including segmentectomy, lobectomy, and pneumonectomy; esophageal surgery such as myotomy and minimally invasive esophagectomy; and minimally invasive cardiac surgery. VATS offers several advantages over thoracotomy. For example, VATS lobectomy results in decreased pain, fewer perioperative complications, shorter chest tube duration, decreased length of stay, faster return to functional status, and decreased inflammatory response [16].

VATS allows operative exposure via small incisions. Importantly, even when limited utility incisions are made, no rib spreading occurs. As with thoracotomy, morbidity is associated with intercostal nerve injury. During VATS, trauma to the intercostal nerve should be minimized by using the smallest port that is feasible, depending on the instrumentation required. An angled, usually 30°, thoracoscope should be used if it prevents pressure on the nerve.

Port insertion should be directed toward the intrathoracic region where the majority of the surgery will occur to avoid using the inferior edge of a rib as a fulcrum for the camera when trying to visualize at difficult angles. Multimodal analgesic strategies should be employed, as for thoracotomy [15]. With shorter lengths of stay and less acute pain, thoracic epidural anesthesia is less frequently required. But it should be considered in patients at increased risk of severe postoperative pain, pulmonary dysfunction, or postthoracotomy pain syndrome [15]. For most patients undergoing VATS, other regional analgesic strategies can be applied, including multilevel injected intercostal nerve blocks, as well as continuous catheter infusion of local anesthetic into the paravertebral extrapleural space providing multilevel intercostal nerve blockade [19].

Wound infections can occur after VATS [42, 43]. As with larger incisions, their incidence can be reduced with appropriate perioperative antibiotic administration, avoiding excessive use of electrocautery, and a layered closure even though the incision is small. Port site implantation of metastases has been reported [44], although its incidence has been virtually eliminated by the routine use of an endoscopic specimen bag when any tissue with malignant potential is extracted.

Sternal incisions

Median sternotomy

Vertical midline sternal division to access the mediastinum is currently the approach utilized for the majority of cardiac surgical procedures. This workhorse incision was first proposed in 1897 by Milton [45]:

> The abdominal and cerebro–spinal cavities and the organs they contain have been freely explored by the surgeon since he has adopted cleanliness with the most brilliant results. The thoracic cavity and its contents, although frequently the seat of surgical interference, have not received the same attention, and no definite lines of technique have so far been laid down. This is partly due to the fact that the thoracic walls present more mechanical difficulties to the surgeon than the abdominal, and partly due to the dread with which interference with most of the thoracic organs still inspires him.

His first report of median sternotomy was for sternal and mediastinal tuberculosis. Although the principles of median sternotomy were described by Milton at the end of the nineteenth century, it remained a seldom used procedure for several decades. Early cardiac interventions were commonly performed via a bilateral transverse thoracosternotomy ("clamshell" incision). In 1953, Shumaker and Lurie's report of pulmonary valvulotomy described their use of a vertical sternotomy [46]. Four years after the first successful open heart operation in 1953, most cardiac surgeons were using bilateral transverse thoracosternotomy. This relatively tedious, time-consuming, painful procedure was replaced for most cardiac operations only after Julian and colleagues

demonstrated the significant superiority of median sternotomy [47]. As noted by Dalton and associates, the modern routine use of median sternotomy for essentially all cardiac operations is "a testimonial to the foresight and practicality of Julian's experience" [48].

Median sternotomy provides anterior mediastinal, bilateral pleural, and lower cervical access. It is ideal in both elective and emergent situations, including thoracic trauma. Median sternotomy, either partial or complete, is indicated for lower cervical procedures including tracheal resection and reconstruction, excision of thyroid or parathyroid masses, lower cervical lymph node dissection, and resection of proximal esophageal masses [49]. Mediastinal pathologic processes, such as tumors and cysts, are accessible via median sternotomy. Superb exposure of the heart and great vessels has made the incision the gold standard for cardiac surgery, particularly when cardiopulmonary bypass is indicated. More recently, the incision has facilitated routine performance of off-pump beating heart coronary bypass operations. Median sternotomy also permits access to the bilateral pleural cavities, permitting pulmonary and hilar exposure without the complications associated with bilateral transverse thoracosternotomy. The utility of sternotomy applies to pulmonary resection [50, 51], lung volume reduction surgery [52], bilateral pulmonary metastasectomy [53], and trauma. When a patient has had prior pulmonary resection via a thoracotomy, reoperative pulmonary resection, particularly completion pneumonectomy, can be performed via median sternotomy, allowing hilar exposure in a field free of adhesions.

The advantages of median sternotomy are numerous. It can be performed rapidly. The incision provides superior exposure to the heart, great vessels, and anterior mediastinum. As a midline access, it permits admission to both pleural cavities. Median sternotomy is safe and heals rapidly. And, since it is less painful than thoracotomy, it compromises pulmonary function less, especially in the early postoperative period, making it an ideal incision for patients with diminished pulmonary capacity [8].

Median sternotomy carries certain disadvantages. The cosmetic result of a vertical midline incision is unappealing to some individuals. While it offers exposure to the anterior mediastinum and bilateral pleural cavities, access to the inferior chest and posterior mediastinum is compromised. Most concerning are the postoperative complications that include sternal instability, sternal osteomyelitis, and mediastinitis. Strategies to minimize these complications are a critical component of the surgical procedure.

The technique of median sternotomy is well established and has changed little since its reintroduction in the 1950s. While there is variability in the details of median sternotomy depending on personal and institutional preferences, certain principles are recognized that are critical to minimize complications. All patients undergoing median sternotomy should have body hair clipped the day of surgery. Routine antibiotic prophylaxis is indicated with the first dose administered intravenously within 1 hour of the incision and postoperative doses discontinued within 24 hours.

The operative technique of median sternotomy and its layered closure play a crucial role in satisfactory healing. The standard incision extends from just below the suprasternal notch to at least, and often just below, the xiphoid, into the linea alba. Precise use of electrocautery on the subcutaneous fat at midline is important to prevent paramedian dissection and to minimize tissue necrosis and subsequent wound infection. The midline of the sternum is identified by palpating the bilateral sternochondral junctions and by visualizing the decussation of the fibers of the pectoralis major muscle. Once the midline of the sternum is defined, the submanubrial and subxiphoid spaces are developed. The superior end of the incision is retracted cephalad and the interclavicular ligament, consisting of fibers of the superior sternoclavicular ligament from each side, is divided. Veins within the suprasternal space should be identified and controlled. Inferiorly, the linea alba is divided, exposing the xiphoid that is then split at midline. The underlying soft tissues, superiorly and inferiorly, are separated from the posterior surface of the sternum with digital dissection, thus diminishing the likelihood of entering the pleura or pericardium when the sternum is cut. The faceplate of the sternal saw is maintained firmly against the posterior sternum, the lungs are allowed to collapse, and the sternum is divided at midline. Alternatively, a Lebsche knife of Gigli saw can be used. Bleeding from the sternal edges is then controlled. Bone wax may be used to control marrow bleeding, although its application may compromise healing. Pinpoint electrocautery is used to control visualized bleeding vessels on the cut anterior presternal fascia. The edges of the posterior sternal fascia are cauterized throughout the length of the sternum. The thymus and pericardium are divided with electrocautery and venous branches at the inferior margin of the innominate vein are controlled. It is imperative to preserve the viability of all presternal tissue. Indiscriminate use of electrocautery may increase tissue necrosis and resultant infection, while discriminate use of electrocautery for median sternotomy has resulted in a wound infection rate of as low as 0.16% [54].

Sternal edges are spread to expose the anterior mediastinum. Sternal retractors, rather than rib spreaders, are designed with blades that distribute the retraction tension evenly along the cut sternal edges, minimizing injury to the sternum [7]. The sternal retractor is not placed too cephalad, where it would risk injury to the innominate vein and brachial plexus. It is opened slowly to minimize sternal and rib fractures and dislocations. Similarly, when exposing the posterior sternal plate, such as during internal mammary artery mobilization, the sternal edges should not be forcefully retracted upward in order to avoid fractures and dislocations.

At the conclusion of the operation, the mediastinal and pleural spaces are drained and the sternal edges are rigidly reapproximated. The sternal edges are again examined for hemostasis. If an internal mammary artery has been harvested, particular attention is directed toward the mammary arterial bed. A variety of methods are described for optimal sternal closure, including stainless steel wires, parasternal sutures, absorbable sutures [55, 56], mersilene

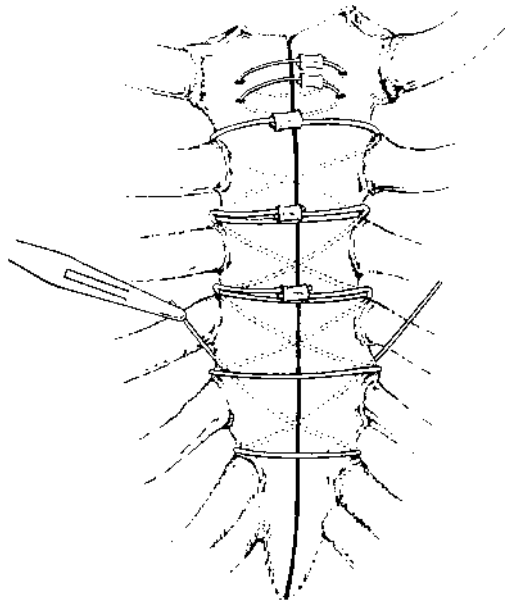

Figure 2.7 An interlocking figure of eight wire suture technique for sternal reapproximation reduced perpendicular wire shear and provides lateral sternal reinforcement. (*Source*: From Ref. [59]; reprinted by permission. Courtesy of Elsevier Science, Inc.)

ribbon [57], and stainless steel bands [58]. Most commonly, six to eight stainless steel wires are placed immediately lateral to the sternal border, to avoid injury to the mammary vessels. Two or three wires are inserted as wide as possible in the manubrium and four or five wires encircle the sternum by placement in the intercostal spaces at the sternochondral junction. In order to minimize postoperative pain, wires are not placed in the sternomanubrial joint, costal cartilage, or ribs. DiMarco and colleagues [59] suggested that interlocking figure of eight sutures may offer a tighter sternal closure by avoiding perpendicular sternal wire shear and allowing lateral reinforcement of the sternal table (Figure 2.7). The wires are twisted by hand, firmly tightened to achieve rigid sternal reapproximation, and buried in the soft tissue to minimize subcutaneous protrusion. Overriding of the sternal edges is strictly avoided. If the sternum is fractured or osteoporotic, a sternal wire weave technique, as described by Robicsek and associates [60], stabilizes the sternal edges providing a more secure closure (Figure 2.8). After sternal reapproximation, the wound is precisely closed in layers. The anterior presternal fascia and the linea alba are closed with a heavy absorbable suture. The overlying soft tissue is then closed to obliterate potential spaces, especially at the inferior aspect of the incision. Some advocate an additional, deep dermal suture, particularly in obese patients, in order to decrease the tension on the skin closure, which may be achieved with either a continuous subcuticular absorbable suture or skin staples.

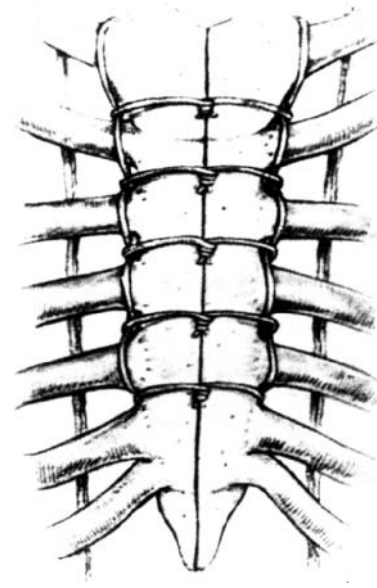

Figure 2.8 The sternal wire weave technique introduced by Robicsek. (*Source*: From Ref. [60]; reprinted by permission. Courtesy of Mosby, Inc.)

Dressings may be left in place at the completion of closure. Alternatively, skin closure with a cyanoacrylate tissue adhesive can act as a barrier to microbial penetration. Obese women or women with large breasts should wear a supportive brassiere or corset postoperatively to minimize lateral tension on the incision. Range of motion exercises of both upper extremities may commence in the early postoperative period, but heavy lifting and strenuous exercise should be avoided for at least 6 weeks after surgery. Sternal nonunion has been observed a year or more after surgery, and is detected by an audible or palpable click on physical examination.

Sternal wound complications are infrequent, occurring after an estimated 0.3–8% of cases, and resulting in increased morbidity and mortality between 10% and 40% [61]. Minor complications include skin separation, as well as superficial soft tissue seroma or infection, without involvement of the bone. These complications can be managed with antibiotic therapy, local drainage and debridement, and frequent wound care (Table 2.1). When the infection is resolved and healthy granulation tissue is present, some practitioners will close the wound secondarily. Major wound complications consist of sternal dehiscence, mediastinitis, and sternal osteomyelitis. They require aggressive management with antibiotics, soft tissue and sternal debridement, and tissue coverage. These can result in grave outcomes. For example, postoperative mediastinitis occurs in 1–3% of those undergoing median sternotomy, and its associated mortality is as high as 40% [62].

A number of factors, preoperative, intraoperative, and postoperative, predispose to sternal complications. Risk factors for sternal wound complications

Table 2.1 Guidelines for the management of median sternotomy complications.

Median sternotomy complication	*Recommended treatment*
Skin disruption, intact anterior presternal fascia	Drainage; debridement; wound care
Intact skin, sternal separation, no infection	Sternal rewiring—Robicsek technique
Skin disruption, sternal separation, no infection	Sternal rewiring; continuous irrigation
Sternal dehiscence, mediastinitis	Sternal debridement; muscle flap coverage or sternal rewiring + continuous irrigation + closure
Chronic sternal osteomyelitis	Partial or complete sternectomy and local coverage

include chronic obstructive pulmonary disease, prolonged intensive care unit stay, respiratory failure, connective tissue disease, and male sex [63]. While preoperative risks such as diabetes, obesity, chronic obstructive pulmonary disease, prior chest irradiation, immunosuppression, and renal failure cannot be eliminated, the surgeon can influence intraoperative issues, such as strict aseptic technique, indicated antibiotic prophylaxis, precise midline sternal division, optimal hemostasis, meticulous layered closure, careful tissue handling, and avoidance of prolonged operative time. Also, postoperative contributors to sternal complications can be minimized, including the need for external cardiac compression, mediastinal bleeding requiring reoperation, and prolonged mechanical ventilation.

The presenting symptoms of sternal dehiscence include significant postoperative incisional pain, skin separation, drainage from the sternal wound, a palpable or audible sternal click, fever, and leukocytosis. Early postoperative sternal instability may result in wound infection as a result of skin separation and bacterial ingress. In severe cases, paradoxical sternal motion may be visible on examination. The condition of a severely unstable, infected sternum results in the physiology of flail chest and cardiac tamponade, resulting in rapid deterioration of respiratory and cardiac function. Aggressive intervention in these critically ill patients is essential in order to reverse a rapidly progressive clinical deterioration characterized by low cardiac output and respiratory failure [64].

Physical examination alone may underestimate the extent of subcutaneous, sternal, and mediastinal involvement. Radiographic evaluation is indicated. Upright posteroanterior and lateral chest radiography, or a sternal series, may demonstrate sternal overriding, separation, or fracture. Fractured sternal wires may also suggest a sternal problem. Also, a midsternal radiolucency on plain chest radiography may be the first indication of sternal separation [65]. However, the finding is not specific in that 30% of patients may develop a midsternal stripe following median sternotomy, in the absence of sternal separation. Rather than conclusively demonstrating sternal separation, the finding of a midsternal stripe warrants thorough clinical evaluation of the operative field. With sternal dehiscence, computed tomography (CT) of the chest may

demonstrate sternal separation, retrosternal fluid collections, or bone destruction suggestive of osteomyelitis.

Sternal wound infection may be demonstrated by microbiologic studies such as Gram stain and cultures with antibiotic sensitivities. Gram-positive bacteria, namely *Staphylococcus aureus* and *S. epidermidis*, are the most frequently implicated microorganisms. Gram-negative flora has also been cultured from infected sternal wounds, including *Pseudomonas*, *Klebsiella*, *Serratia*, and *Enterobacter* species. Increasingly, antibiotic-resistant bacteria, for example, methicillin-resistant *S. aureus* (MRSA) and vancomycin-resistant *Enterococcus* (VRE) are the offending organisms. Broad-spectrum systemic antibiotics are initiated empirically, and then adjusted as microorganisms and their antibiotic sensitivities are identified.

When sternal dehiscence is associated with wound infection, key therapeutic principles apply: wide wound drainage, aggressive debridement, coverage of the wound with viable tissue, respiratory support, nutritional optimization, and prolonged antibiotic administration. If sternal dehiscence is diagnosed early, while the sternum is still viable and deep infection into the mediastinum has not occurred, an attempt at sternal rewiring employing the Robicsek weaving technique [66] can be considered (Figure 2.8). Prior to sternal closure, the mediastinum is copiously irrigated with antibiotic or an antiseptic agent such as povidone iodine. Merrill and colleagues [62] employed continuous postoperative irrigation with excellent results. After satisfactory soft tissue and bony debridement, a superior irrigation catheter and one or more mediastinal drains were inserted, and then the sternum, soft tissue, and skin were reapproximated. All patients underwent high-volume mediastinal irrigation with at least 100 mL/hour for a minimum of 7 days, using either antibiotic or antiseptic solution. Of 40 reported patients with postoperative mediastinitis, all survived and 38 achieved complete healing of the wound without further operative intervention or major complication as a result of the one-stage procedure. If the attempted one-stage approach is unsuccessful, or if radical sternal debridement results in inadequate bone remaining for stable closure, then tissue coverage with a muscle or omental flap is indicated [67–69]. Often, sternal involvement is more extensive than initially anticipated. Cartilage or bone resorption secondary to chondritis or osteomyelitis mandates removal of much, if not all, of the sternum. Ideally, preoperative multidisciplinary planning, including the involvement of reconstructive plastic surgeons, may facilitate efficient, even single stage, coverage. A variety of options for coverage of the anterior mediastinum are available (Table 2.2), with the pectoralis major or rectus abdominis as the first-line option, with the pectoralis favored between the two. The omentum is often thought of as the second-line treatment choice [70].

Chronic osteomyelitis does not carry the rapidly progressive clinical deterioration associated with the acute condition. However, it is also a grave complication, particularly in patients with prosthetic valves. A prolonged antibiotic regimen lasting 4–6 weeks may control the infection. Yet it is frequently

Table 2.2 Available tissue transfer for coverage of the anterior mediastinum following sternal debridement.

Left and/or right pectoralis major muscle or myocutaneous flap
Left and/or right rectus abdominis muscle or myocutaneous flap
Left or right latissimus dorsi muscle or myocutaneous flap Omentum
Free muscle transfer (rectus abdominis or latissimus)
Skin and soft tissue of anterior chest wall

prudent to intervene earlier with partial or total resection of the infected sternum and adjacent cartilage and ribs. As with the acute process, muscle flap coverage may be required to achieve coverage of mediastinal structures. Less extensive infection may be related to a foreign body such as a suture or sternal wire, resulting in chronic draining sinuses. Management consists of antibiotic therapy based on cultures obtained from the drainage sites. Local debridement of the involved sternal region may be required, along with removal of the infected foreign body, followed by local tissue coverage.

Sternal nonunion, with partial separation of the sternum in the setting of intact soft tissue and skin coverage, may occur long after the operation (Figure 2.9). To reapproximate the parts simply by suturing them together usually fails due to the preexisting gap, often resulting in reseparation [66]. Here, a modification of Robicsek's weaving method is recommended. The lower portion of the sternum is exposed, up to the level where the sternum is solid. An osteotomy is made on one side of the sternum to allow realignment of the edges. Weaving wires are placed lateral to the sternum and three or four transverse wires are buttressed by the parallel parasternal weave. Pectoralis muscles are detached laterally and approximated at midline over the sternal closure.

Incisional hernias occur in 4% of patients undergoing median sternotomy. Typically, they are located in the linea alba, immediately inferior to the xiphoid. Risk factors for postoperative ventral hernia include wound infection, obesity, and pulmonary complications. In one report, 35% of hernias became symptomatic and required repair [71].

Complications after median sternotomy occur in the pediatric population and similar principles of management used in adults are applicable, with distinct exceptions. In particular, when reconstructing sternotomy wounds in female children, wide mobilization of the pectoralis major muscle should be avoided in order to prevent injury to the undeveloped breast buds [72]. It may be more appropriate to cover the defect with limited mobilization of the sternal edge of the adjacent pectoral cutaneous tissue, or a rectus abdominis muscle or myocutaneous flap.

While median sternotomy is not as painful as posterolateral thoracotomy, it is not painless and inadequate pain control can contribute to complications. Poor respiratory function can prolong the requirement for mechanical

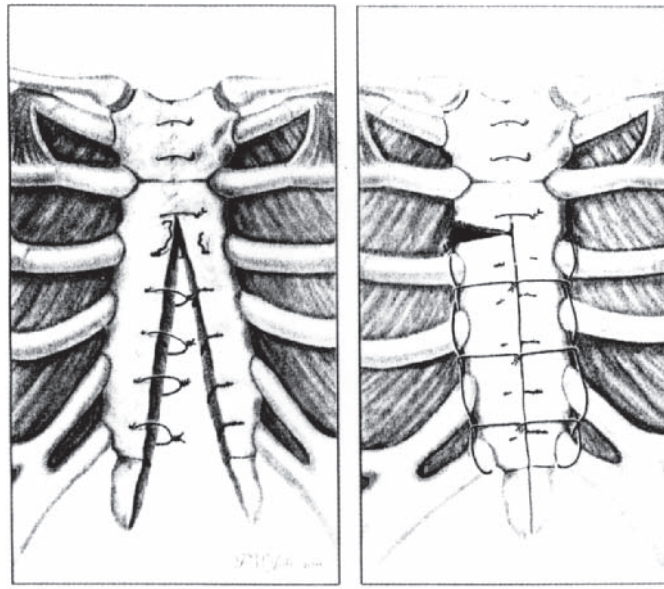

Figure 2.9 Modified sternal weave for partial sternal nonunion. (a) Before repair. (b) After repair. (*Source*: From Ref. [66]; reprinted by permission. Courtesy of Mosby, Inc.)

ventilator support and can increase the risk of pulmonary complications including pneumonia and need for reintubation. The use of opioid analgesics is associated with respiratory depression, nausea, vomiting, decreased gastrointestinal motility, and peripheral vasodilation, all of which can contribute to complications, prolonged lengths of stay, and increased costs [73]. Improved pain control has numerous demonstrable physiologic benefits. Multimodal analgesia, the combination of different modes of analgesia delivery, is superior to any single method of reducing pain. After sternal reapproximation with wires, two catheters with multiple side opening can be placed anterior to the sternum, brought out through small incisions, and connected to a pressurized elastomeric pump. Continuous catheter delivery of local anesthetic via infusion with an elastomeric pump can decrease narcotic analgesia requirement after median sternotomy [73].

Reoperative sternotomy

Reoperative sternotomy is employed for cardiac and other thoracic pathology that requires reoperative intervention. With the growing number of individuals requiring second, or more, coronary revascularization, the need for this surgical approach has increased. Reoperation is also necessary for patients who have undergone prior valve surgery and need reintervention for prosthetic valve complications or who require valve replacement after previous

commissurotomy or valve repair. The use of reoperative sternotomy is particularly prevalent among the pediatric population who need corrective operations for congenital cardiac defects after prior management with palliative procedures. Reoperative sternotomy is required for heart transplantation in patients who have had prior cardiac surgery. The operative approach is also utilized for mediastinal or bilateral pleural surgery after prior median sternotomy for cardiac or pulmonary pathology.

Reoperative sternotomy differs in several ways compared to the standard median sternotomy. When reoperative sternotomy is planned, special attention should be directed to a thorough history and physical examination. The previous operative report must be reviewed to verify the technical details of the earlier procedure, including whether mammary arteries were used and where all bypass grafts were placed. A lateral chest radiograph will provide the surgeon with an estimate of the proximity of the anterior heart to the posterior table of the sternum. If the heart is close to the sternum, a chest CT may define the location where difficulties might be expected when opening the sternum [8]. Clips placed along the mammary artery may be visible on plain radiographs, verifying the course of the graft. The number of sternal wires, as well as their method of placement, should be assessed.

In the operating room, the surgeon must be prepared for an emergency, including hemorrhage or ventricular fibrillation. Blood should be immediately available. It is prudent to place percutaneous defibrillator pads in the event that ventricular dysrhythmias occur during dissection of the heart from the adjacent structures. It is also prudent to insert a guide wire in a femoral artery prior to reoperative sternotomy to facilitate prompt arterial access should emergent cardiopulmonary bypass or intraaortic balloon pump placement be required.

The scar from the prior sternotomy incision is used for entry in the reoperation. The sternal wires are identified and may be removed. However, some advocate retaining the wires after untwisting them to allow upward traction on the sternum in order to limit the depth of penetration of the sternal saw [74]. Also, when using the sternal saw, minimizing ventilator tidal volumes and positive end-expiratory pressure (PEEP) limits the displacement of the heart toward the sternum [72]. Typically, the sternum is divided with an oscillating saw. Occasionally, a Lebsche knife is employed. The suprasternal space is dissected, exposing the superior surface of the manubrium. Inferiorly, the linea alba and xiphoid are exposed. The costal arch and xiphoid are retracted upward and laterally to allow the retrosternal space to be dissected under direct visualization. The anterior table of the sternum can then be divided with the oscillating sternal saw. The posterior sternal table is then divided in a similar manner, under direct visualization, starting at the inferior portion of the sternum. With continued upward traction on the sternal edges, the mediastinal structures are gently dissected off the posterior sternum, continuing laterally to the pleural reflections. It may be worthwhile to enter the pleural cavity to facilitate exposure in a space relatively free of adhesions. Once the sternum

is completely divided, a sternal retractor can be inserted and gently spread. The heart and great vessels are then exposed. It may be advisable to institute cardiopulmonary bypass prior to total mobilization of the heart, allowing the heart to be arrested to minimize injury and bleeding from epicardial surfaces.

Complications of reoperative sternotomy are related to damage to structures during initial dissection, as well as compromised sternal healing postoperatively. Injuring native coronary vessels or bypass grafts can result in hemodynamic instability and hemorrhage. Massive bleeding can occur with major cardiac lacerations. Also, minor injuries can result in intraoperative bleeding once heparinization has occurred. Thus, all surfaces should be carefully examined before bypass and after heparin reversal. If the sternum is brittle or fractured, figure of eight wires should be placed around the sternum. If it is osteoporotic, or the sternotomy is not midline, the Robicsek technique [60] should be considered, providing lateral reinforcement and minimizing tension on the sternum (Figure 2.8).

Bilateral submammary vertical sternotomy

The vertical skin incision for routine median sternotomy is cosmetically unappealing, principally at the superior end. The sternal skin also appears susceptible to a higher rate of hypertrophied and keloid scar formation [75]. Alternative skin incisions to expose the sternum include low midline vertical, Y-shaped, and bilateral submammary approaches. Proponents for each incision emphasize the superior cosmetic outcome and that the exposure is not compromised. The bilateral submammary incision is particularly favorable in females. With the patient in the supine position, the incision is created along the inferior mammary fold of both breasts and then joined transversely. Dissection of the flaps, including subcutaneous and breast tissue, allows exposure of the entire sternum. In a report of 40 female patients undergoing open heart surgery, the exposure of the mediastinum was excellent, and there were no difficulties in cannulating the ascending aorta for cardiopulmonary bypass [76]. Closed suction drains should be placed under the flaps to avoid fluid collections. Complications associated with this incision are insignificant if close attention is paid to details.

Partial sternotomy

Certain procedures in the anterior mediastinum do not require the complete exposure of the mediastinum that is obtained by full sternotomy. An upper partial sternotomy allows resection of masses in the anterior mediastinum including thyroid and parathyroid lesions, as well as exposure of the trachea and proximal esophagus. It can be modified to expose the ascending aorta and arch. A vertical incision is made from the suprasternal notch to the sternomanubrial joint (angle of Louis). The dissection is carried down to the anterior table of the manubrium and the suprasternal space is exposed as for a standard median sternotomy. After digital dissection in the retromanubrial plane and division of the interclavicular ligament, the manubrium is divided

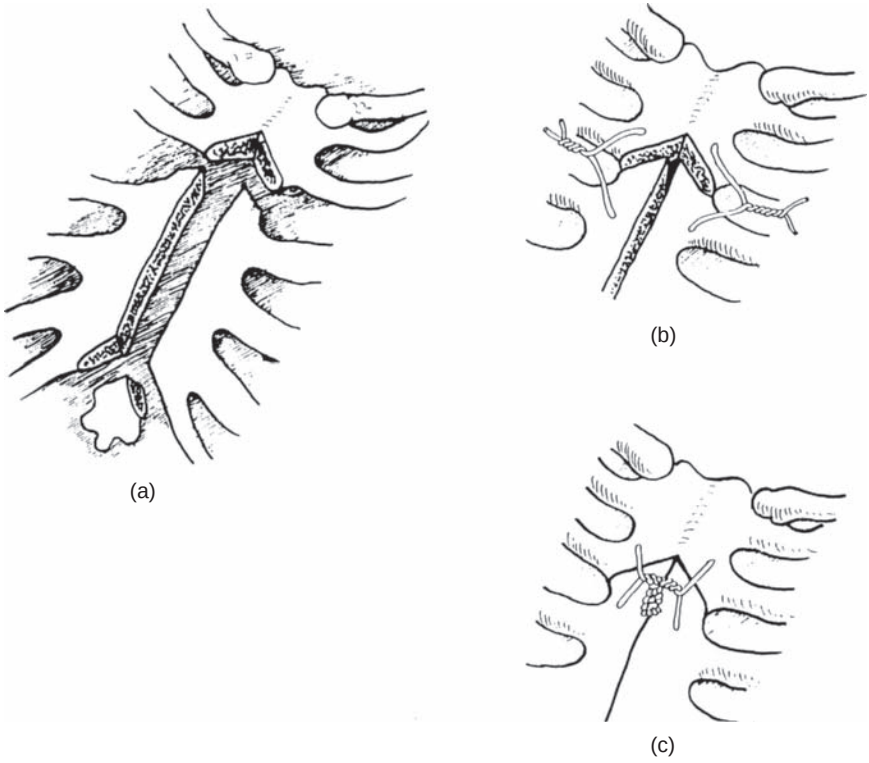

Figure 2.10 Lower partial sternotomy. (a) Only the sternal body is divided vertically. The manubrium can be transected in an inverted V-shaped line while the xiphoid can simply be resected. (b, c) The sternum is closed with paired wires. (*Source*: From Ref. [80]; reprinted by permission. Courtesy of Mosby, Inc.)

at midline from the superior edge of the manubrium to the sternomanubrial joint using the Lebsche knife or sternal saw. In the sternomanubrial joint, the Lebsche knife can be rotated 90° to then gently open the joint laterally, avoiding extending the transection more laterally into the internal mammary vessels. A small rib spreader, Tuffier or pediatric, opens the manubrium exposing the anterior mediastinum. The upper partial sternotomy can be combined with a collar incision for wide, T-shaped, cervicothoracic exposure [77]. Postoperative drainage can be achieved with closed suction. The manubrial edges are reapproximated with two wires and the sternomanubrial joint is closed with vertically placed wires.

The heart can be exposed with lower partial sternotomy [78, 79]. The sternum is divided vertically from the xiphoid to the sternomanubrial joint and the joint is opened bilaterally. The manubrium can be transected along an inverted V-shaped line to facilitate aortic cannulation and prevent horizontal dislocation during sternal closure [80]. The xiphoid can also be simply resected. Coronary bypass surgery, resection of left ventricular aneurysms,

valve procedures, repair of atrial and ventricular septal defects, and resection of atrial myxomas are some of the operations that can be safely performed via this incision. A standard sternal retractor is utilized. Exposure of the aorta and superior aspect of the operative field can be optimized by elevating the manubrium as the sternal edge is lifted during internal mammary artery harvest. The sternal edges are reapproximated with standard parasternal wire placement while the sternomanubrial joint is secured with two vertical wires (Figure 2.10).

The clear advantage of the partial sternotomy, when it is technically appropriate for exposure, is diminished postoperative pain compared to a full sternotomy or anterior thoracotomy. In the lower sternotomy, both clavicular heads, as well as the attachments of the first and second ribs, remain intact. In both the upper and lower partial sternotomy, the incision is shorter. Also, with the upper partial sternotomy, the body of the sternum remains intact, without risk of sternal dehiscence or nonunion. Potential disadvantages to the partial sternotomy include the possibility of dividing bilateral mammary vessels, inadequate exposure to the aortic arch in lower partial sternotomy, and the need to rewire three sternal segments instead of two.

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CHAPTER 3

Arrhythmias following Cardiac and Thoracic Operations

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Cardiac arrhythmias after thoracic surgery are not a new problem. Since the first reports in 1943 [1, 2], many communications concerning arrhythmias have appeared in the literature. They may originate in the atrium or the ventricle, although supraventricular arrhythmias are far more common, usually accounting for over 80% of such disorders. Of these, atrial fibrillation occurs most frequently, although multifocal atrial tachycardia and atrial premature complexes also occur. The purposes of this chapter are (i) to describe the incidence and characteristics of cardiac arrhythmias that appear after cardiac and thoracic surgery, (ii) to discuss the etiology of these dysrhythmias, (iii) to report on prophylactic regimens thought to be effective against them, and (iv) to describe their treatment.

Incidence and characteristics of postoperative arrhythmias

Cardiac arrhythmias, particularly atrial arrhythmias such as atrial fibrillation or flutter, occur in approximately 25–40% of patients undergoing open heart surgery [3]. The incidence of these arrhythmias following noncardiac thoracic surgery is more variable, depending upon the specific procedure. In 2007, Mayson and colleagues noted that atrial fibrillation complicates between 3% and 30% of noncardiac thoracic surgeries, and between 16% and 46% of cardiac surgeries [4].

Most studies that have addressed the issue concluded that postoperative arrhythmias serve as a marker for increased mortality, longer intensive care unit stay, and longer length of hospital stay [5–7], although it is not clear if the arrhythmia itself is an independent predictor or rather a symptom of the patient's illness.

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Supraventricular arrhythmias

In a summary for the American College of Chest Physicians (ACCP) 2005 symposium on postoperative atrial fibrillation after cardiac surgery, Hogue and associates noted that the reported rates range from >30% for patients undergoing coronary artery bypass surgery to nearly 60% for patients having combined coronary artery bypass grafting and mitral valve surgery [8]. The arrhythmia typically occurs on postoperative days 2 to 3 with 70% of events occurring within the first 4 postoperative days.

As displayed in Table 3.1, atrial arrhythmias following thoracic surgery appear in 8–37% (average 20%) of all patients undergoing thoracotomy. Atrial fibrillation is by far the most common rhythm, accounting for at least 55% of supraventricular arrhythmias. The magnitude of operation plays an important role. After simple exploration or biopsy, anywhere from 4.6% to 23.5% (average 9.3%) of patients suffered an atrial arrhythmia. After lobectomy, the incidence ranged from 1.6% to 59.1% (average 11.6%), and after pneumonectomy, atrial arrhythmias appeared in 3.3–40.0% of patients (average 18.0%). After thoracotomy for esophagectomy, the incidence of supraventricular arrhythmias varied from 4.4% to 23.8% (average 17.6%).

Atrial arrhythmias following pneumonectomy are particularly worrisome. In a series of 236 consecutive pneumonectomies reported by the Mayo Clinic, 22% of patients experienced postoperative atrial arrhythmias, most often

Table 3.1 Postoperative cardiac arrhythmias following general thoracic surgery.

Study	*Patients*	*% with Arrhythmias*	*% Atrial*	*% Ventricular*
Amar *et al*. [7]	100	13	100	0
Amar *et al*. [20]	78	13	100	0
Amar *et al*. [22]	100	18	100	0
Amar *et al*. [32]	70	23	100	0
Asamura *et al*. [10]	267	25	89	6
Bayliff *et al*. [34]	99	67	90	10
Borgeat *et al*. [19]	30	20	67	33
Borgeat *et al*. [33]	30	26	57	43
Harpole *et al*. [6]	136	24	100	0
Keagy *et al*. [29]	369	20	81	15
Krowka *et al*. [9]	236	22	100	0
Ritchie *et al*. [30]	140	37	69	18
Roth and Meyer [17]	75	8	100	0
Von Knorring *et al*. [21]	598	16	100	0
Wahi *et al*. [5]	197	23	100	0
	(Total patients)		←(Averages)→	
	2525	22	92	8

Key: %Atrial = Percentage of all patients with arrhythmias who demonstrated atrial fibrillation, atrial flutter, or other supraventricular tachycardia. %Ventricular = Percentage of all patients with arrhythmias who demonstrated premature ventricular contractions, bigeminy, or ventricular tachycardia or fibrillation.

atrial fibrillation (64%) [9]. In 55% of patients, the arrhythmia was persistent despite attempts at chemical and electrical cardioversion. In patients with refractory atrial fibrillation, 31% died during their hospitalization. Overall, 25% of patients in this series experiencing any kind of postoperative arrhythmia died within 30 days of surgery. This was independent of preoperative pulmonary function, postoperative diagnosis, cancer stage, or arterial blood gas levels. Intrapericardial dissection and postoperative pulmonary edema increased the incidence of postoperative dysrhythmia, suggesting that cardiac manipulation and irritation may predispose to morbidity and mortality.

These arrhythmias typically appear within the first 3 days of thoracic surgery, with a peak incidence around the second day [6, 10]. Almost all will resolve spontaneously, as 90% disappear within the first three postoperative days, and 7.9% of the remainder will discontinue within the first week.

Ventricular arrhythmias

Ventricular arrhythmias, mainly appearing as either bursts of extrasystoles or short runs of nonsustained tachycardia, are occurring more commonly as the acuity of illness and average patient age increase with time. Fortunately, they are much more rare than supraventricular arrhythmias, appearing in only 0–43% (average 6%) of all patients undergoing thoracic surgery of all types.

Risk factors

Many investigators have attempted to determine the specific risks factors associated with postoperative cardiac arrhythmias. Unfortunately, no common element has emerged.

Risk following cardiac surgery

Heintz and Hollenberg surmised in 2005 that initiating factors for an arrhythmia following surgery include transient insults such as hypoxemia, cardiac ischemia, catecholamine excess, or electrolyte abnormality [11]. That same year, the ACCP published a symposium on postoperative arrythmia, specifically postcardiac surgery atrial fibrillation [8]. They provided more detail but no additional substantiation suggesting that the problem is multifactorial and may never be fully elucidated. They pointed out that the electrophysiologic substrate for postoperative reentrant atrial fibrillation may be preexisting or may develop due to heterogeneity of refractoriness after surgery. Ectopic beats originating in the pulmonary veins explain at least some episodes of postoperative atrial fibrillation. Many factors have been identified as being associated with postoperative atrial fibrillation, but the most consistent variable across studies is increasing patient age. It is speculated that age-related pathologic changes in the atrium contribute to arrhythmia susceptibility.

Multiple perioperative factors may contribute to arrythmia including operative trauma, inflammation, elevations in atrial pressure possibly due to

left ventricular diastolic dysfunction, autonomic nervous system imbalance, metabolic and electrolyte imbalances, or myocardial ischemic damage incurred during the operation. One modifiable risk factor for postoperative atrial fibrillation is the failure to resume therapy with beta-adrenergic receptor blockers after surgery.

Murphy and colleagues identified some interesting factors during a randomized trial of off-pump coronary artery bypass [12]. In the trial, there was a significant reduction in the incidence of postoperative atrial fibrillation in the off-pump group (11% vs. 45%, $p < 0.001$). Multivariate regression analysis identified cardiopulmonary bypass and cardioplegic arrest as the only independent predictors of postoperative atrial fibrillation (OR 7.4; 95% CI 3.4–17.9). This study suggests that the inflammatory responses to bypass, myocardial ischemia, and atrial cannulation are significant contributory factors to the development of atrial fibrillation following cardiac surgery.

Similar results were obtained in another randomized trial by Matthew and associates in an observational study of 4657 patients undergoing CABG surgery between November 1996 and June 2000 at 70 centers located within 17 countries [13]. They noted risk factors associated with atrial fibrillation were advanced age, history of atrial fibrillation, chronic obstructive pulmonary disease, valve surgery, and postoperative withdrawal of a beta-blocker or an angiotensin-converting enzyme (ACE) inhibitor.

Risk following general thoracic surgery

In one study by Melendez and Carlon of 180 patients undergoing pneumonectomy, lobectomy, wedge resection, or lesser pulmonary procedures, there was a 12% incidence of cardiac "complications" [14]. The authors attempted to assign a cardiopulmonary risk index (CPRI: the addition of the Goldman cardiac risk index [15] to a pulmonary risk index that included obesity, cough, elevated $PaCO_2$, poor spirometric parameters, cigarette smoking, and asthma) to each patient. There was no correlation between the CPRI and the incidence of cardiac arrhythmias. Furthermore, there was no correlation between postoperative arrhythmias and either the cardiac risk index or the pulmonary risk index when considered in isolation. Not too surprisingly, however, preoperative "rhythm alteration," "cardiac disease," an abnormal electrocardiogram, and a forced expiratory volume in 1 second (FEV_1) <2.0 correlated positively with postoperative arrhythmias.

This finding was echoed by Hasenbos and colleagues who compared differences in postoperative complications between patients given epidural or intramuscular narcotic pain medication [16]. Although this study found no differences in postoperative complications between groups according to method of pain relief, it did find that patients who were taking "cardiac drugs" preoperatively had a higher risk of developing arrhythmias in the postoperative period (68% vs. 38%). Roth *et al*. attempted to quantify coronary artery calcifications found on chest computed tomography (CT) scan and use the coronary artery calcification index (CAC) to predict the occurrence of

postoperative arrhythmias [17]. Although the CAC had 100% sensitivity for postoperative arrhythmias, its positive predictive value was only 23%, making it a weak index by which to screen patients for this complication. With a negative predictive value of 100%, however, it is helpful to know that a patient with no coronary calcifications present on chest CT will probably have a smoother postoperative course.

Asamura and associates have undertaken the most complete study to date on preoperative risk factors for postoperative arrhythmias [9]. They studied 267 patients undergoing pneumonectomy, lobectomy, bilobectomy, segmentectomy, or wedge resection, and 63 patients developed arrhythmias (23.6% incidence). Of those, 60 (95%) were supraventricular, and of that subset, 33 (55%) were atrial fibrillation. Besides tabulating demographic variables such as sex, age, indication for operation, hypertension, and preoperative ECG status, the authors also made note of the mode of thoracotomy, the extent of the pulmonary resection and the extent of the lymph node dissection. They found that only age >70 years ($p < 0.0008$) and extent of pulmonary resection ($p < 0.0001$) were independent predictors for the appearance of postoperative atrial arrhythmias.

There is evidence emerging that the side of operation may play a role in the genesis of arrhythmias following thoracic surgery, particularly pneumonectomy. In a series of 115 patients undergoing pneumonectomy, Yellin and Zeligson reported the incidence of dysrhythmias to be 4.2% in patients undergoing a left-sided operation, compared with 14% in those with a right pneumonectomy ($p = 0.05$) [18]. This has been supported by some studies [6], but not by others [5, 19].

Influence on outcome

Murphy and colleagues in a randomized trial of off-pump coronary artery bypass discovered that blood usage, postoperative pneumonia, inotrope requirements, and hospital and intensive care unit stay were associated with patients having atrial fibrillation [12]. However, since postoperative atrial fibrillation often develops in patients with comorbidities who are predisposed to other complications and prolonged hospitalization, it is unclear whether the prevention of postoperative atrial fibrillation will result in improved patient outcomes, particularly shorter hospitalizations.

Development of postoperative atrial fibrillation is associated with a higher risk of operative morbidity, prolonged hospitalization, and increased hospital cost compared with that in patients remaining in sinus rhythm. A few studies have attempted to correlate the occurrence of postoperative arrhythmias with patient outcome. In a report of 78 patients undergoing pneumonectomy, lobectomy, or wedge resection for nonsmall cell lung cancer, Amar *et al*. found a 13% incidence of postoperative dysrhythmias [20]. Somewhat surprisingly, neither the stage of the tumor, the extent of operation, nor the administration of preoperative radiation therapy influenced survival at the 30-month

follow-up. This may have been due to the small study population. Survival at 30 months was, however, adversely affected by age >70 years, perioperative chemotherapy, and the occurrence of postoperative supraventricular tachycardia. The patients who died during the follow-up period did so as a result of their disease, and not from arrhythmias.

In another study conducted by von Knorring and associates on 598 patients undergoing resection for lung cancer, atrial tachyarrhythmias occurred in 16% [21]. Of those patients with recurrent episodes, 17% died. This was significantly higher than the mortality rate observed in patients with limited episodes (2.5%, $p < 0.01$).

Specific arrhythmias and their mechanisms

It is not currently known what causes atrial dysrhythmias in postoperative thoracic surgical patients. There are many conjectures, including increased sympathetic discharge from postoperative pain, atrial fluid overload from intraoperative and postoperative resuscitation, and even increased atrial pressure from high pulmonary vascular resistance in patients after parenchymal resection. In a study of 100 consecutive patients undergoing pulmonary resection at Memorial Sloan–Kettering Cancer Center, Amar *et al*. were able to show that patients with high right ventricular pressures determined by echocardiography had a higher incidence of postoperative supraventricular tachycardias [22]. This was not associated with an elevated right atrial pressure, however, as measured by a central venous catheter. Also, the right and left atrial chambers were of normal size and did not differ between groups.

These findings are partially supported by the work of Reed *et al*., who showed that right ventricular function is diminished following pulmonary resection [23]. They demonstrated that right ventricular end diastolic volume increased and ejection fraction decreased during the first 2 days after resection. In comparison with preoperative values, pulmonary artery systolic pressure and calculated pulmonary vascular resistance did not change. This corresponds to the period of highest risk for postoperative supraventricular tachycardia. They did not follow these patients out beyond the first 2 days, however. Also, for the 20% of patients who exhibited supraventricular tachycardia, they did not discriminate the right ventricular variables between patients who suffered supraventricular tachycardia and those who did not. Whether this results from a primary myocardial process or an alteration in right ventricular loading during the early postoperative period remains unclear. The same authors subsequently reported that right ventricular preload recruitable stroke work was unchanged during the first 24 hours following surgery, which suggests that right ventricular contractility *per se* is unaffected [24].

Atrial premature contractions

Atrial premature contractions are characterized by a P wave appearing earlier in the cardiac cycle than anticipated, usually of a different morphology

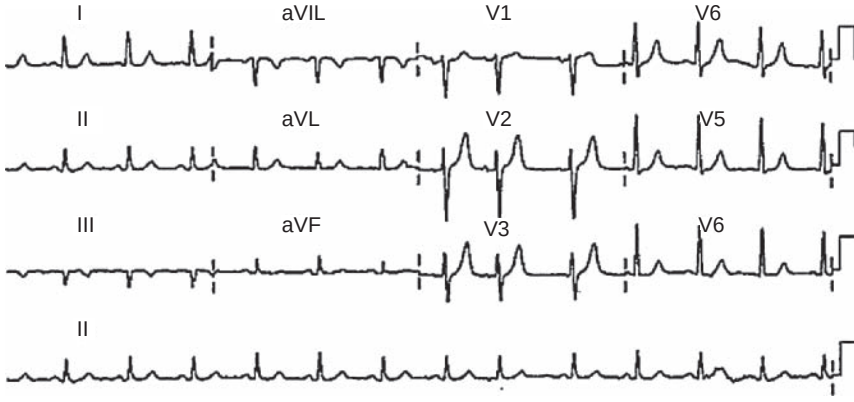

Figure 3.1 Electrocardiogram demonstrating atrial premature contractions characterized by a P wave appearing earlier in the cardiac cycle than anticipated, usually of a different morphology than the usual sinus P waves.

than the usual sinus P waves (Figure 3.1). This suggests that the ectopic beat originates in atrial tissue outside of the sinoatrial node. If the atrial premature contraction is early, it may encounter a refractory atrioventricular node, and either no impulse will be transmitted to the ventricle or the conducted impulse will depolarize the ventricle with a bundle branch pattern. If the atrial premature contraction enters the sinus node during electrical diastole, it may "reset" the node and delay onset of the next sinus beat.

The causes of atrial premature contractions are legion, and they have been associated with congestive heart failure, electrolyte imbalances, myocardial ischemia, and pericarditis. The use of temporary epicardial atrial wires or a transesophageal electrocardiogram can facilitate their diagnosis.

Atrial fibrillation

Atrial fibrillation is a chaotic, disorganized, and irregular beating of the atrium at 400–600 times per minute. The sinus node no longer participates in the pacemaking process. The atrioventricular node, which is incapable of transmitting impulses so rapidly to the ventricle, blocks most of these beats. The ventricle therefore responds to atrial fibrillation by beating irregularly between 60 and 180 beats per minute, usually in the more rapid range (Figure 3.2). This results in the electrocardiographic hallmark of an undulating baseline with irregular, narrow QRS complexes.

The subjective effect on the patient ranges from little more than a feeling of "doom" or palpitations to frank hypotension and syncope. Treatment should be therefore tailored to each individual situation, depending upon the immediacy of the desired result.

Most episodes of atrial fibrillation will resolve spontaneously within a few days of surgery. In fact, as discussed above, less than 10% of patients who experience postoperative atrial fibrillation will remain in it beyond 1 week.

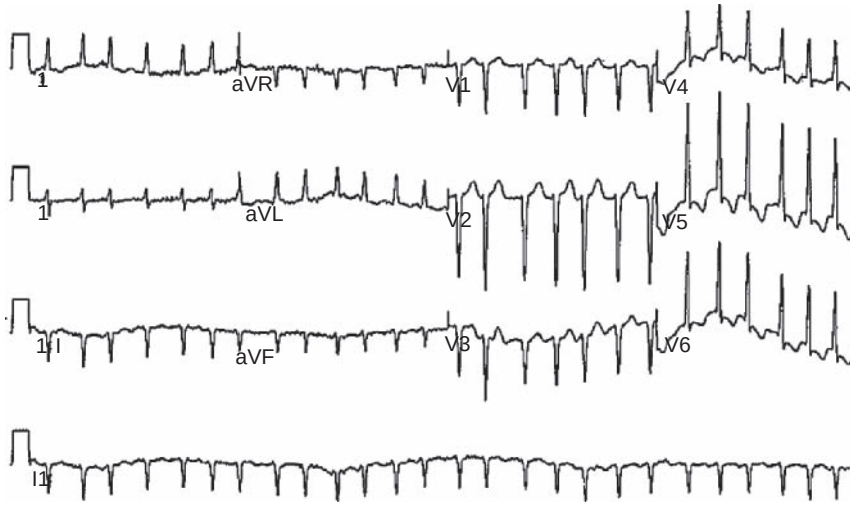

Figure 3.2 Electrocardiogram and rhythm strip demonstrating atrial fibrillation with an undulating baseline with irregular, narrow QRS complexes.

Therefore, it is uncommon to have to continue antiarrhythmic drugs beyond the first few days after surgery, even if their administration was required to convert the arrhythmia back to sinus rhythm.

Atrial flutter

Atrial flutter is much less commonly encountered following thoracic surgery. It is a "well-organized" arrhythmia, with the atrium beating in a more regular, synchronous fashion at 200–400 beats per minute. The AV node can only transmit every second or third beat to the ventricle, usually resulting in a regular ventricular rate of 140–150 beats per minute (Figure 3.3). There is classically

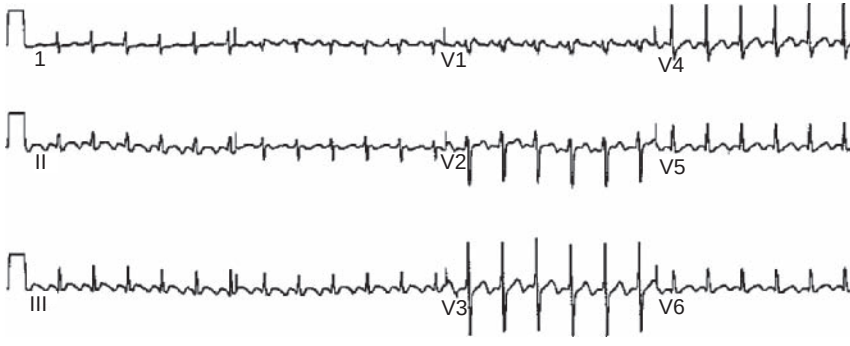

Figure 3.3 Electrocardiogram demonstrating atrial flutter with a classic "sawtooth" or "F wave" pattern in limb leads II, III, and aVF.

a "sawtooth" or "F wave" pattern in limb leads II, III, and aVF. If the diagnosis is not clear, maneuvers to temporarily block the AV node (carotid sinus massage, Valsalva maneuver, or adenosine) will usually be helpful. Hemodynamically, this arrhythmia is usually better tolerated than atrial fibrillation, but occasionally ventricular rate control is required in order to allow more time for diastolic filling and ejection. Because atrial flutter is less common than atrial fibrillation, less is known about its natural history. It stands to reason, however, that atrial flutter in the postoperative period should follow the same time course as atrial fibrillation, as the immediate stimulus for this arrhythmia abates with time.

Multifocal atrial tachycardia

Multifocal atrial tachycardia is an arrhythmia often associated with chronic obstructive pulmonary disease, a disorder common to many patients undergoing thoracic surgery. Therefore, its appearance may be due to either the stimulus of surgery or as a baseline rhythm disturbance. Its cause is unknown and its treatment nonspecific. It is defined as a rhythm with an atrial rate of between 100 and 200 beats per minute with at least three different P wave morphologies. The R–R and P–R intervals will usually vary, as there are multiple pacemaking sites in the atrium, each a different distance from the AV node (Figure 3.4). Multifocal atrial tachycardia may degenerate into atrial fibrillation.

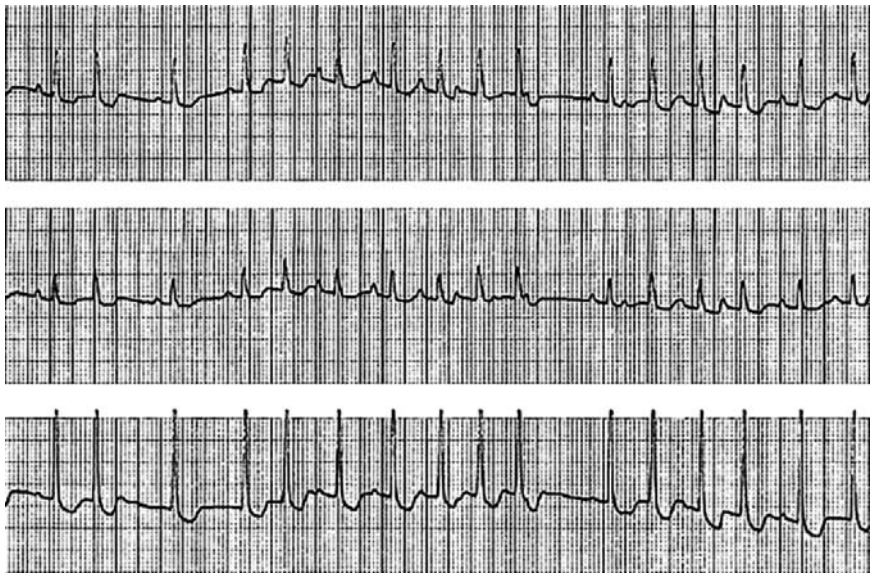

Figure 3.4 Rhythm strip demonstrating multifocal atrial tachycardia. The R–R and P–R intervals usually vary due to multiple pacemaking sites in the atrium, each a different distance from the AV node.

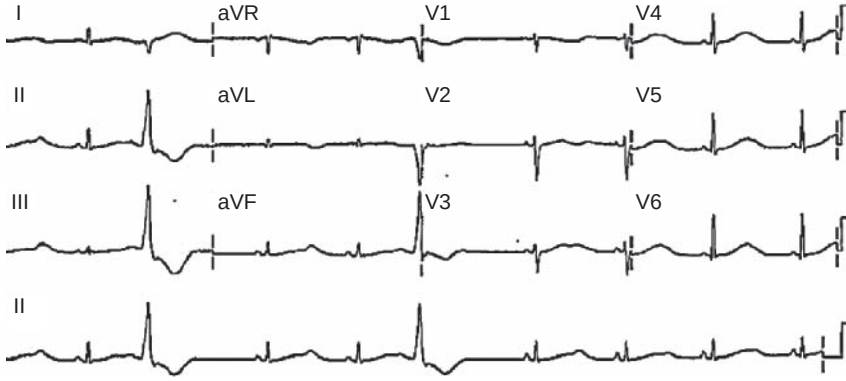

Figure 3.5 Electrocardiogram demonstrating a premature ventricular complex. The QRS complex is wide and bizarre, mimicking a bundle branch pattern of conduction. There is no relationship to the P wave.

Premature ventricular complexes

Premature ventricular beats or complexes are fortunately much less common in the postoperative period than are supraventricular rhythms (Figure 3.5). Their origin is more often traced to myocardial ischemia and/or electrolyte disturbances, which induce microreentrant circuits in small areas of abnormal ventricular myocardium. The QRS complex is wide and bizarre, mimicking a bundle branch pattern of conduction. There is no relationship to the P wave. If the premature ventricular complex conducts in a retrograde manner through excitable tissue such as the AV node and SA node, then these pacemakers may be "reset," and a compensatory pause will appear.

Premature ventricular complexes may be classified as unifocal, one morphology, or multifocal if there are two or more morphologies. This implies that unifocal premature ventricular complexes arise from a single locus in the ventricle, whereas multifocal ectopic beats arise from several sites. Occasionally, as mentioned above, a supraventricular impulse may encounter refractory conducting tissue and appear similar to a premature ventricular complex. If the bizarre QRS complex is preceded by a P wave and there has been a long–short sequence of R–R intervals, then it is likely that an atrial premature contraction or other supraventricular ectopic beat has encountered refractory conduction tissue. This is known as Ashman's phenomenon.

Ventricular tachycardia

Ventricular tachycardia is defined as three or more consecutive beats of ventricular origin at a rate of greater than 100 beats per minute. They are always wide-complex beats with no relationship to the P wave (Figure 3.6). Although it may sometimes be difficult to discriminate ventricular contraction from supraventricular contraction with aberrant conduction, ventricular tachycardia typically will not terminate with vagal maneuvers, and is

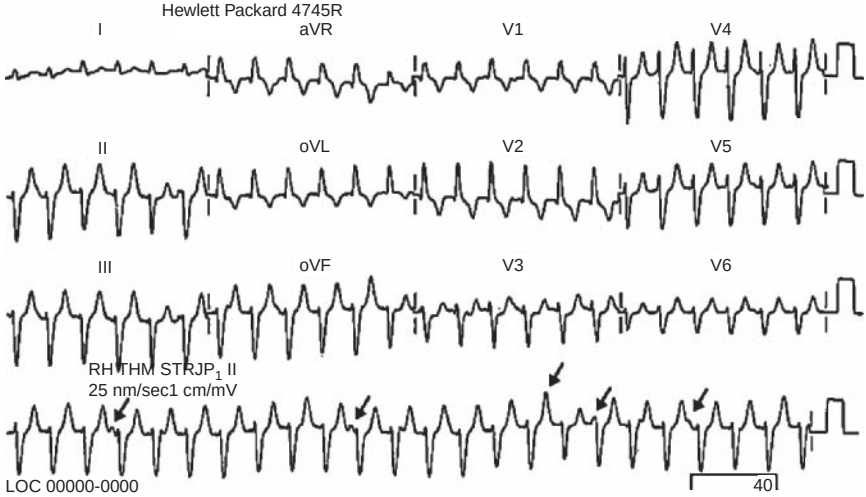

Figure 3.6 Electrocardiogram and rhythm strip demonstrating ventricular tachycardia. They are always wide-complex beats with no relationship to the P wave.

almost always associated with hemodynamic collapse. Therefore, resuscitation is paramount, and diagnosis can be established after a stable rhythm has returned.

Antiarrhythmic drug prophylaxis

Since the description of postoperative arrhythmias, there have been attempts to prevent them. Multiple drug trials have appeared in the literature, ranging from randomized, prospective studies to retrospective chart reviews. The results are mixed.

Amiodarone

Amiodarone, which possesses all four of the Vaughan-Williams classifications of antiarrhythmic drug action (sodium channel, calcium channel, potassium channel, and β-adrenergic receptor blockade), has been used increasingly frequently as an agent against atrial arrhythmias. Unfortunately, amiodarone is associated with thyroid, ophthalmic, and pulmonary toxicities. Van Meighem *et al*. tested amiodarone as a prophylactic agent against postoperative arrhythmias following pulmonary surgery but terminated their study after 3 of 96 patients developed life-threatening adult respiratory distress syndrome (ARDS), with a mortality of 67% [25]. This did not seem to result from toxic levels of amiodarone, as these patients demonstrated similar serum levels of drug to patients without complication. In a review of their experience from 1987 to 1991, 552 major pulmonary resections had been performed, with an overall incidence of atrial fibrillation between 16% and 23%. The incidence of ARDS

in patients receiving amiodarone was 11%, compared with 1.8% in patients who did not receive this drug. This particular adverse effect has not yet been reported in the cardiac surgical population, in whom amiodarone has been shown to effectively halve the rate of postoperative atrial fibrillation [26–29].

Digoxin

Prophylactic digitalization has been attempted to minimize the occurrence of postoperative arrhythmias, both in cardiac and in noncardiac thoracic surgical patients. In a randomized controlled unblinded study of 80 consecutive patients undergoing thoracotomy for esophagectomy, Ritchie *et al*. randomly assigned half of the patients to receive digoxin and half to receive no treatment [30]. The drug was begun preoperatively and continued postoperatively for 9 days, with serum levels measured and adjusted appropriately. There was no difference in the occurrence of dysrhythmias between the patient groups. The authors did not discriminate between atrial and ventricular arrhythmias. They did, however, clearly demonstrate that patients undergoing resection for benign disease had a significantly lower incidence of arrhythmia than did those having an operation for malignancy (0% vs. 39%, $p < 0.002$). They extended their findings in a study of 140 patients undergoing thoracotomy for pulmonary and esophageal procedures [31]. The overall incidence of arrhythmias was 37%, with no differences between digoxin-treated patients and control. Within the past 10 years, there have been no significant trials of digoxin either in cardiac or thoracic surgery.

Diltiazem

In a small study of patients undergoing pneumonectomy at Memorial Sloan–Kettering Cancer Center, digoxin was compared with diltiazem for postoperative control of arrythmias [22]. Patients on digoxin had an incidence of 31% supraventricular arrythmias while those on diltiazem had an incidence of 14% ($p = 0.09$). However, in the subset of patients having an intrapericardial pneumonectomy, diltiazem patients had no supraventricular arrythmias compared with 32% in the digoxin arm ($p < 0.005$). No patients in the study had ventricular tachycardia, although most had occasional ventricular premature beats.

Flecainide

In a randomized, placebo-controlled single-blinded study of 30 patients undergoing pneumonectomy, lobectomy, or decortication, Borgeat *et al*. determined that flecainide administration immediately following operation resulted in a significant decrease in the use of additional antiarrhythmic drugs [19]. Because these authors did not consider the incidence of atrial arrhythmias as a separate end point, one cannot draw a conclusion about the efficacy of flecainide against this rhythm. There was, however, a significant decrease in the incidence of PVCs. In another study by this same group comparing the postoperative administration of flecainide with digoxin, the same group

showed that flecainide significantly decreased the incidence of atrial fibrillation (by 50%) and PVCs (by 100%) [29].

Propranolol

In 1999, Bayliff and associates conducted a randomized trial of propranolol versus placebo in patients undergoing a major pulmonary resection [34]. This study was somewhat flawed because of a large number of patients (142 out of 242) who did not participate in the study. They were able to randomize 99 of the 100 patients in the study. Patients in the experimental arm received 10 mg of propranolol every 6 hours. Arrythmias of any variety occurred in 62% of placebo patients and 72% in the propranolol group. However, rhythms that required treatment were 20% in the placebo patients and 6% in the propranolol patients. Only atrial fibrillation occurred in the propranolol group while every rhythm including ventricular tachycardia was seen in the placebo group. Hypotension and bradycardia were common in the propranolol group at 49% and 25%, respectively, while both were significantly less in the placebo group at 26% and 4%, respectively. Although it seemed to be effective, the side effects argue against the routine use of propranolol in thoracic surgery.

Cardiac surgical drug prevention trials

In 2005, the ACCP published a symposium that included a detailed review of pharmacologic preventative measures in cardiac surgery [35]. They reviewed 91 trials that had a primary study design of a randomized, controlled trial of one drug versus placebo/usual care. Pharmacologic therapies that are reviewed include Vaughan-Williams class II agents (i.e., beta-receptor antagonists) (29 trials; 2901 patients), Vaughan-Williams class III agents (i.e., sotalol and amiodarone) (18 trials; 2978 patients), Vaughan-Williams class IV agents (i.e., verapamil and diltiazem) (5 trials; 601 patients), and Vaughan-Williams class I agents (i.e., quinidine and procainamide) (3 trials; 246 patients), as well as digitalis (10 trials; 1401 patients), magnesium (14 trials; 1853 patients), dexamethasone (1 trial; 216 patients), glucose–insulin–potassium (3 trials; 102 patients), insulin (1 trial; 501 patients), triiodothyronine (2 trials; 301 patients), and aniline (1 trial; 32 patients). A consistent finding was that antiarrhythmic drugs with beta-adrenergic receptor-blocking effects (i.e., class II beta-blockers, sotalol, and amiodarone) demonstrated successful prophylaxis. Furthermore, those therapies that did not inhibit beta-receptors generally failed to demonstrate a decreased incidence in postoperative atrial fibrillation. While sotalol and amiodarone have been shown in some studies to be effective, their safety and the incremental prophylactic advantage in comparison with beta-blockers have not been conclusively demonstrated. They concluded with a recommendation that strong consideration should be given to the prophylactic administration of Vaughan-Williams class II beta-blocking drugs as a means of lowering the incidence of new onset postoperative cardiac surgery atrial fibrillation.

Novel methods of arrhythmia prevention

Included in the ACCP supplement on postoperative cardiac surgery atrial fibrillation was a report by Maisel and associates concerning the use of biatrial pacing [36]. They reviewed nine randomized controlled trials addressing prophylactic atrial pacing after cardiac surgery to prevent atrial fibrillation. Prophylactic right atrial pacing and prophylactic left atrial pacing have yielded inconclusive results. Prophylactic biatrial pacing (BAP) reduced the incidence of atrial fibrillation significantly in four studies, reduced it nonsignificantly in one study, and had no effect in another study. On the basis of the literature that was reviewed and graded for quality, it was concluded that prophylactic atrial pacing to prevent atrial fibrillation after cardiac surgery is safe and may be effective.

Another novel idea was reviewed by Howard and Barnes [37]. They found evidence to suggest that statins may also reduce the risk of postoperative cardiac surgery atrial fibrillation. Numerous studies in nonsurgical cardiovascular patients have found reduced rates of atrial fibrillation with statins. In patients who have undergone coronary artery bypass grafting, several observational studies have also documented benefit. One randomized controlled trial reported a significant reduction in the risk of atrial fibrillation and reduced length of hospital stay in patients given preoperative atorvastatin beginning 7 days before surgery. Ongoing research suggests that statins may reduce the risk of atrial fibrillation through pleiotropic effects independent of cholesterol lowering such as reductions in inflammation, oxidative damage, neurohormonal activation, and thrombosis.

Treatment of new onset supraventricular arrhythmias

Because arrhythmias are more common in postoperative cardiac surgery, most published studies and guidelines focus on that group of patients. However, the strategies are similar for general thoracic surgery patients. A brief review of the most commonly used medications is presented in Table 3.2.

Dunning and associates, on behalf of the EACTS Audit and Guidelines Committee published guidelines in 2006 [38], suggested a treatment algorithm that has been adapted and presented in Figure 3.7. Because atrial arrhythmias are far more common, their management is discussed here. Ventricular arrhythmias are rare after thoracotomy. Their treatment relies primarily upon resuscitation of the hemodynamically unstable patient, as outlined in standard ACLS protocols. The principles of correcting electrolyte abnormalities and ruling out myocardial ischemia should be paramount for patients demonstrating ventricular ectopy or tachycardia or both.

Once the diagnosis of an atrial tachyarrhythmia has been established, the first priority is to assess hemodynamic stability. In addition, one should maintain oxygenation, assess fluid balance, and assess the serum potassium. If the patient experiences syncope, or if the blood pressure is less than 80 mm Hg systolic, then the options are chemical conversion or synchronous electrical

Table 3.2 Commonly used antiarrhythmic agents.

Drug	*Class*[a]	*Loading dose*	*Maintenance dose*
Adenosine	(Unassigned)	6–12 mg rapid i.v. push	(None)
Digoxin	(Unassigned)	1.0–1.5 mg (4 doses/ 12 hours)	0.125–0.25 mg/day p.o. or i.v.
Procainamide	I-A	17 mg/kg (load over 20 minutes)	2 mg/min i.v. infusion
Sotolol	III	80 mg bid	120 mg bid
Ibutilide	III	1 mg i.v. over 10 minutes	(None)
Diltiazem	IV	0.25 mg/kg (load over 10 minutes)	5–10 mg/min i.v. infusion
Amiodarone	(Unassigned)	150 mg i.v. over 10 minutes	1 mg/min for 6 hours, then 0.5 mg/min for 18 hours; convert to 800–1600 mg/day

[a]Vaughan-Williams classification.

cardioversion. For DC conversion, the first shock is typically delivered at 200 joules (J), with subsequent shocks at 300 and 360 J, respectively.

Ventricular rate control

If the patient is hemodynamically stable and mentating, then one should control the ventricular rate to allow better ventricular filling and an optimum ejection fraction. Drugs such as digoxin, verapamil, diltiazem, or metoprolol all depress atrioventricular nodal conduction and are most useful here. Many thoracic surgical patients exhibit bronchospasm, however, and therefore beta-adrenergic blocking drugs are relatively contraindicated. For these reasons, amiodarone has become the most common agent followed by diltiazem, sotolol, and digoxin. Details of dosing are listed in Table 3.2. If these drugs are not successful, or if the patient's hemodynamic condition deteriorates, then synchronous cardioversion should be undertaken immediately. Once rate control has been achieved, the patient may be changed to equivalent doses of oral amiodarone over the next 24 hours.

During this period, electrolytes such as potassium and magnesium should be assayed and replaced as needed. Myocardial ischemia should be ruled out by electrocardiography. In the absence of these factors, the natural history of postoperative atrial tachyarrhythmias is self-termination. Therefore, usually nothing more than a day or two of rate control is required. If the patient spontaneously converts to normal sinus rhythm over the next 24 hours, the medication can be discontinued and no further treatment is required.

Chemical/electrical cardioversion

If the patient remains in a rate-controlled fibrillation or flutter beyond 24 hours, then cardioversion should be attempted after performing

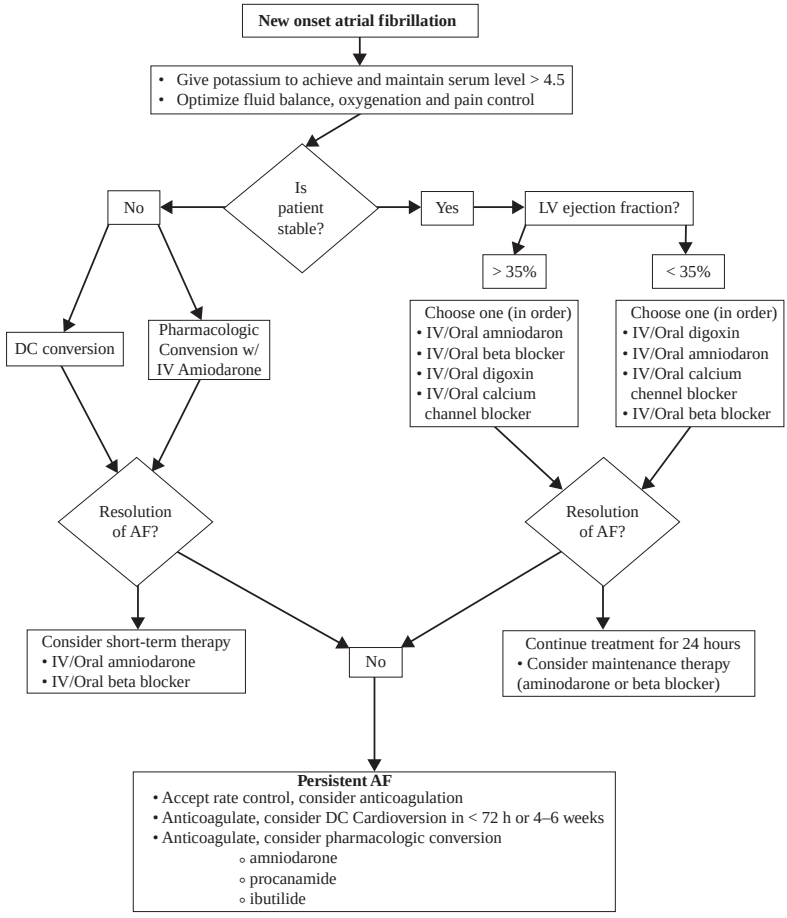

Figure 3.7 Algorithm for the management of new onset postoperative atrial fibrillation (*Source*: Adapted from Ref. [38]).

echocardiography to exclude the presence of intracardiac thrombus. Usually this is begun as a trial of chemical cardioversion with antiarrhythmic medication. Unfortunately, there is no single drug that demonstrates high efficacy at converting postoperative atrial fibrillation or atrial flutter to sinus rhythm. The class I-A agents, such as procainamide and quinidine, exhibit approximately a 30% conversion rate, similar to placebo. The class I-C agents, such as flecainide and propafenone, claim a somewhat higher conversion rate (about 40–60%), but their use is contraindicated following a recent myocardial infarction or in patients with a known depressed ejection fraction. The new class III agent ibutilide claims a very high conversion rate of approximately 60% but is associated with both a high relapse rate and the appearance of malignant ventricular arrhythmias such as torsades de pointes. One of the older

class III agents, D-sotalol, has been shown to be effective at converting atrial fibrillation to sinus rhythm, but the racemic mixture of D- and L-sotalol has significant beta-blocking activity and is relatively contraindicated in thoracic surgical patients.

Amiodarone has become the most popular drug for cardioversion, particularly since it is relatively safe in patients with depressed ventricular function. Although amiodarone causes pulmonary fibrosis when used chronically, postoperative atrial fibrillation is short lived and self-limited so that exposure to amiodarone is limited. The usual dosing is intravenous (i.v.): 5–7 mg/kg over 30–60 minutes, then 1.2–1.8 g/day continuous i.v. or divided oral doses until 10 g total. The usual maintenance dose is 100–400 mg/day. Its short- and long-term toxicities include bradycardia, visual disturbances, nausea, phlebitis (if given i.v.), constipation, hepatic, ocular, pulmonary, thyroid, and neurologic toxicity. Torsade de pointes ventricular tachycardia is less common than with dofetilide, ibutilide, or sotalol.

Martinez and colleagues reviewed the pharmacologic management of post-cardiac surgery supraventricular arrhythmias [39]. Of the 128 articles that they evaluated on the topic of atrial fibrillation after cardiac surgery, only 19 studies dealing with pharmacologic heart rhythm control were relevant. There were limited data guiding treatment for the rhythm control of atrial fibrillation following cardiac surgery in patients who do not require urgent cardioversion. They suggested that the choice of an antiarrhythmic drug needs to be guided by patient characteristics. Based on limited available evidence, amiodarone is recommended for pharmacologic conversion of postoperative atrial fibrillation and atrial flutter in patients with depressed left ventricular function who do not need urgent electrical cardioversion. This recommendation is made largely because of the effectiveness of amiodarone and also because of its relatively favorable side effects profile. Sotalol and class 1A antiarrhythmic drugs are reasonable choices for patients with coronary artery disease who do not have congestive heart failure. There are no definitive data to guide the decision about the duration of antiarrhythmic drug therapy for patients with atrial fibrillation following cardiac surgery. Most protocols continue therapy with the antiarrhythmic drug for 4–6 weeks following surgery, but evidence from randomized studies is lacking.

Postepisode management and discharge planning

If the patient who has had multiple episodes of atrial arrhythmias converts to sinus rhythm, then the oral antiarrhythmic drug should be continued for at least 30 days after surgery. It may be stopped in the outpatient setting, because the risk of relapsing into atrial fibrillation or atrial flutter is extremely unlikely so late after the operation. If the arrhythmia persists, however, the patient should anticoagulated with heparin and then maintained on warfarin. Semielective electrical cardioversion may be undertaken at this time, with adequate serum levels of antiarrhythmic drug present using echocardiographic guidance.

Although there is very little information in the surgical literature about the incidence of stroke from left atrial thrombus released in postoperative atrial fibrillation, one can derive a strategy from the literature on all patients with atrial fibrillation. As a group, patients with nonvalvular atrial fibrillation carry about a sixfold increased risk of thromboembolism compared with patients in sinus rhythm [40]. Other factors are additive to the relative risk of stroke including previous stroke (RR = 2.5), diabetes mellitus (RR = 1.7), hypertension (RR = 1.6), heart failure (RR = 1.4), and advanced age (RR = 1.4). On the other hand, postoperative atrial fibrillation usually is self-limited with permanent conversion occurring within 6–12 weeks. In general, anticoagulation is not recommended for new onset postoperative atrial fibrillation unless the patient has an overwhelming number of risk factors. The ACCP taskforce cautioned that any decision should be weighed against the potential for bleeding diathesis while on anticoagulation [4].

Typically, if patients are discharged from the hospital in rate-controlled atrial fibrillation with adequate anticoagulation, they will spontaneously convert to sinus rhythm as outpatients. If, however, they remain in atrial fibrillation beyond 30 postoperative days, then they should be offered outpatient electrical cardioversion, providing they have remained therapeutically anticoagulated.

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CHAPTER 4

Complications of Cardiopulmonary Bypass and Cardioplegia

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Introduction

Although cardiopulmonary bypass (CPB) and the use of cardioplegia for myocardial protection are used routinely today in the practice of cardiovascular surgery, these are both relatively new techniques. The potential utility of extracorporeal circulation was recognized in 1813, when Le Gallois wrote the following:

> But if the place of the heart could be supplied by injecting and if, with a regular continuance of this injection, there could be furnished a quantity of arterial blood, whether naturally or artificially formed, supposing such a function possible, then life might be indefinitely maintained in any portion.
>
> [1]

Bruchonenko was the first to suggest that extracorporeal circulation might be useful clinically. Using a circuit with a roller pump and excised canine lungs for oxygenation, he was able to support the arrested canine heart for several hours. A pump circuit of this design was later used for successful valvular heart surgery in animal models in the 1930s and early 1940s.

Credit for the first successful clinical use of a pump oxygenator, the forerunner of today's modern CPB machine, goes to John H. Gibbon, Jr, M.D. His vision for this device dates to 1930 when he was caring for a patient who died of massive pulmonary embolism. At that time, he wrote the following:

> During the 17 hours by this patient's side, the thought constantly recurred that the patient's hazardous condition could be improved if some of the blue blood in the patient's distended veins could be continuously withdrawn into an apparatus where the blood could pick up oxygen and discharge carbon dioxide and then pump this blood back into the patient's arteries.
>
> [1]

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Gibbon also recognized the importance of heparin, which became available in sufficient quantities only in the late 1930s. Development of his pump oxygenator continued during the 1940s in laboratory animals. Even at this early stage, the potential complications associated with CPB were recognized by Gibbon and he made refinements related to the problems of hemolysis, air embolism, and the unwanted effects of a blood–surface boundary. The first clinical use of his pump oxygenator took place in 1952 in an infant with suspected atrial septal defect. The attempted use of the pump oxygenator in this patient and two other early patients were unsuccessful. The first successful operation using the pump oxygenator took place on May 6, 1953, when an atrial septal defect was repaired using a 26-minute period of extracorporeal support [2].

As more complex cardiac operations became possible with the use of the pump oxygenator, it became apparent that there were still limitations imposed by the beating heart and the return of bronchial blood into the operating field. The technique of intentional cardiac arrest imposed by the injection of potassium chloride solution dates to animal studies from the early 1900s [1]. Melrose was the first to report in 1955 the technique of induced cardioplegic arrest of the heart during heart surgery, using injection of potassium citrate solution, or cardioplegia, directly into the aortic root after cross-clamping of the aorta [3]. The alternative technique of retrograde, or coronary sinus cardioplegia, was introduced by Lilehei who reported its use during an aortic valve replacement in 1956 [4]. Both of these techniques have come into widespread clinical usage.

The development and clinical application of CPB and modern techniques of myocardial protection have allowed a wide array of cardiopulmonary operations that would not otherwise be possible. These techniques, however, are associated with a variety of complications and pathophysiologic consequences that affect nearly every patient in whom they are applied. This chapter focuses on the complications associated with the clinical use of CPB and myocardial protection and are presented in five sections: (i) the mechanics of CPB and related complications; (ii) monitoring for CPB and related complications; (iii) anticoagulation for CPB and related complications; (iv) the pathophysiologic consequences of CPB; and (v) the complications of cardioplegia. The reader is referred to other excellent texts on cardiac surgery in adults [5], the techniques of CPB [6–8], and cardiothoracic anesthesia [9, 10] for additional information.

Mechanics of CPB and related complications

Components of the CPB circuit and related complications

CPB is used to facilitate many cardiac operations today. Although the features of the CPB circuit and the conduct of CPB will vary from institution to institution, and may vary with the special requirements dictated by a particular operative procedure, many features are common to all applications [11]. A typical CPB circuit is presented in Figure 4.1. Many of the mechanical

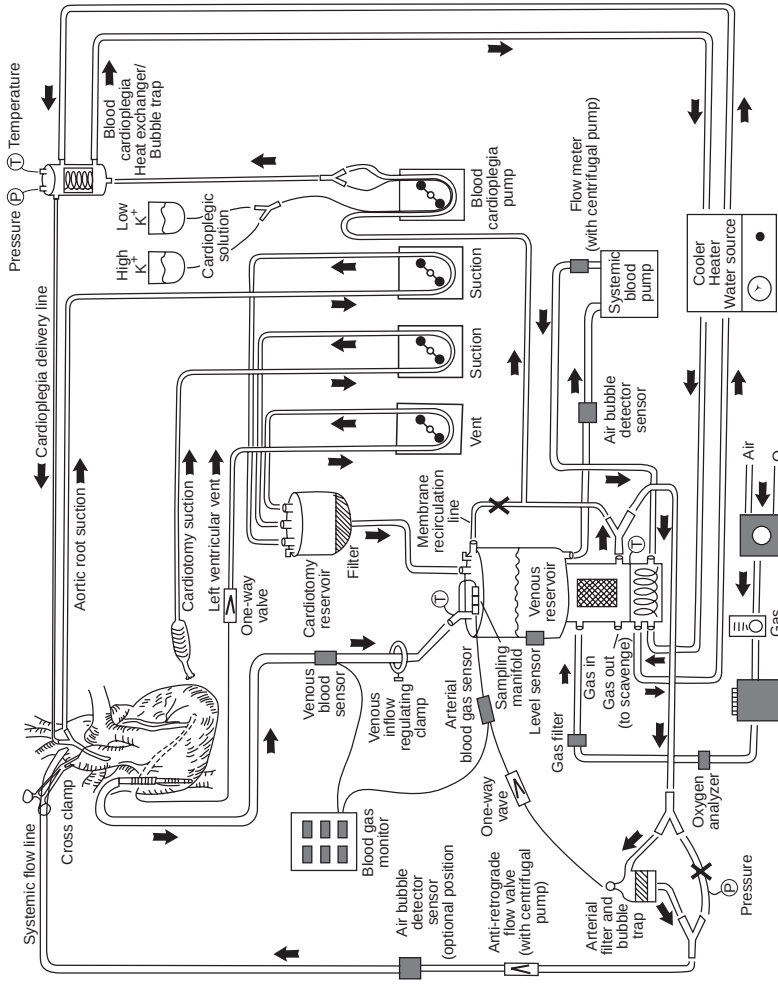

Figure 4.1 A typical cardiopulmonary bypass circuit. (*Source*: From Ref. [11], p. 70, with permission from LWW.)

complications associated with the use of CPB are related to the individual components of the circuit.

Venous cannulas

Venous cannulas are available in a variety of designs, materials, and sizes, and are often categorized as either one-stage (atrial) or two-stage (cavo-atrial). The venous cannulas may be wire-wound or made from hard synthetic materials to prevent kinking. Thin metal, rather than thicker plastic, tips may increase the effective size of a given cannula. The simplest method for atrial cannulation is with a single venous cannula (either one-stage or two-stage). For most operations in which the right side of the heart is entered, however, bicaval cannulation is required. With bicaval cannulation, caval occlusion, often with umbilical tape secured around the cannulas, provides a clear operative field for operations on or through the right side of the heart.

Venous cannulation

During venous cannulation, atrial arrhythmias or untoward hemodynamic effects may be caused by manipulation of the heart. This is particularly true if the heart must be retracted leftward and superiorly for placement of IVC cannulation sutures. These hemodynamic effects are usually transient, but electrical cardioversion for atrial arrhythmias may be necessary and the necessary equipment should be available during cannulation. The potential for arrhythmias may be increased if the systemic temperature is allowed to drift too low during opening and cannulation. In situations in which bicaval cannulation will be used, IVC purse-string sutures can be placed and cannulation can be performed after CPB is initiated (i.e., with only SVC cannulation) to help avoid hemodynamic difficulties. Incisions in the atrium or vena cavae should be made carefully to prevent inadvertent extension of these incisions and unwanted bleeding. One's fingers should be used to confirm the correct position of the venous cannulas during insertion. Without proper care, venous cannulas may be placed inadvertently in a variety of locations, including the innominate vein, the hepatic veins, the coronary sinus, or even through a septal defect to the left side of the heart. Caval tapes should be used carefully because they may tear or lacerate the atrium or vena cavae, particularly with retraction (i.e., as for mitral valve operations). After the termination of CPB, cannulation incisions in the SVC should be closed carefully to prevent narrowing of the SVC [12]. This problem can be avoided in many situations by inserting the SVC cannula through a purse-string in the right atrial appendage. Inadvertent narrowing of the cannulation incision is usually not a problem for incisions in the right atrium.

Preexisting central venous or pulmonary artery catheters may be displaced or dislodged during cannulation. The surgeon must be aware of this possibility and the anesthesiologist must monitor for this type of complication. On rare occasion, purse-string sutures may entrap or injure one of these catheters

and may necessitate reoperation for removal of the affected catheter [13, 14]. Transesophageal echocardiography (TEE) may sometimes be useful to identify these problems [14]. With the use of caval occlusion tapes, monitoring lines caught between the tape and the venous cannula may be rendered useless temporarily or even damaged permanently. In practice, it may be helpful to "pull back" the pulmonary artery catheter before caval tapes are tightened and then advance the catheter once again when the caval tapes are released.

During venous cannulation, it is important for the surgeon to be aware of the possibility of a persistent left superior vena cava (LSVC). This anomaly is present in approximately 0.5% of the general population, but it is more common in patients undergoing cardiac surgical procedures, and particularly those with congenital heart disease. When a two-stage venous cannula is used, the presence of a persistent LSVC is not usually a problem. When the right heart must be entered and bicaval cannulation is used, the extra return of blood through the coronary sinus may pose difficulties, however. If the innominate vein is normal in size, the persistent LSVC may simply be occluded during CPB. If the innominate vein is small or absent, occlusion of the persistent LSVC during CPB may produce venous hypertension and possibly neurologic injury. Alternative approaches in this situation include the use of a cardiotomy suction device placed in the orifice of the coronary sinus through the open right atrium or direct (retrograde) cannulation of the persistent LSVC and the use of an occlusion tape around this vessel.

Venous air embolism may occur during insertion of venous cannulas [15]. If an intracardiac shunt is present, this situation may potentially result in systemic air embolism.

Before CPB is initiated, the presence of venous cannulas in the right atrium may obstruct the ordinary venous return to the heart and interfere with proper hemodynamics. This unwanted side effect is most pronounced with bicaval cannulation. If obstruction to proper venous flow produces persistent hemodynamic instability, CPB should be initiated immediately.

Peripheral venous cannulation (rather than direct atrial cannulation) may be useful in circumstances such as cardiopulmonary arrest outside of the operating room, during redo operations before the repeat sternotomy, and in certain aortic surgery procedures. In these circumstances, the use of as large a venous cannula as possible will help to facilitate adequate CPB. When possible, a peripheral venous cannula should be advanced into the right atrium, using either palpation, measurement of the length of the cannula, or TEE to guide proper placement. A variety of commercially available thin-walled cannulas, often with guide wire or other introducer systems, are available for use in this situation. When peripheral vessels are cannulated under direct vision using a cutdown approach, special care should be used after decannulation to close the venotomy without narrowing the vessel, in an effort to reduce the risk of venous thrombosis.

Venous reservoir and drainage

When a membrane oxygenator is used, the venous reservoir is placed in the circuit immediately before the pump. This device also serves as a gross bubble trap for all blood that returns to the perfusion circuit from the venous line and from cardiotomy suction lines. The venous reservoir may be constructed of heavy plastic or a collapsible plastic bag. Advantages of the heavy plastic variety include ease of measuring blood volume in the reservoir, ease of priming, and the ability to attach a vacuum suction for assisted venous drainage, if desired. The collapsible type may be advantageous because it eliminates some of the blood–air interface and may help to prevent inadvertent air embolism. The collapsible type is more susceptible to damage (i.e., tearing), however. Regardless of the type of venous reservoir, this device provides the perfusionist a ready source for volume infusion into the patient and also a safety margin if the venous return is interrupted during CPB.

In most applications of CPB, the venous drainage is accomplished simply by siphon effect (due to gravity) to the venous reservoir that is placed below the level of the patient. The amount of venous drainage is affected by (i) the height of the patient above the venous reservoir, (ii) the central venous pressure, and (iii) the resistance of the venous cannulas and circuitry. The relationship between the central venous pressure and these factors is given by

$$P_{\text{vsys}} = \text{f}\left(\frac{Q,\ \text{Viscosity}}{\text{cannula size, venous line size, venous line suction}}\right)$$

where P_{vsys} is the mean systemic venous pressure and Q is the systemic blood flow [16]. The goal during CPB is to maintain the systemic venous pressure as low as possible. Inadequate venous drainage will limit the ability of the perfusionist to maintain an adequate flow rate and can be due to one or more related factors. The venous drainage can be improved by (i) elevating the patient in relation to the venous reservoir, (ii) increasing the venous cannula size (the sum of the cross-sectional areas of all venous cannulas in use), (iii) increasing the diameter of the venous line, or (iv) by the use of venous line suction.

Augmented venous drainage

The technique of augmented venous drainage may be useful in a variety of clinical situations, but is particularly useful when long, relatively narrow venous cannulas are needed (e.g., for minimal access procedures). Two general techniques are available. In the first technique, either a roller or a centrifugal pump is placed in the venous line between the patient and the venous reservoir. When a roller pump is used, the perfusionist must be careful to monitor the pump speed continuously to prevent the buildup of excessive negative pressure that may cause the right atrium or great veins to collapse around the cannula. The use of a centrifugal pump may decrease this risk. In either case, a "shunt" placed around the pump may reduce the risk of excessive negative pressure. The venous line pressure should be measured near the pump

and kept less than −60 to −100 mm Hg [17]. The second general technique involves the application of a vacuum directly to the venous reservoir. This approach is simpler and avoids the use of a second pump. Application of 20–60 mm Hg vacuum to the venous reservoir is usually adequate and safe.

Although augmented venous drainage may facilitate operative procedures that would otherwise be more difficult, there are several potential risks. The most obvious problem relates to the increased risk of air entry into the venous circuit from holes in the heart or around the venous cannulas. Air may also enter the heart through central venous catheters or introducer sheaths that may be in place [18]. In most circumstances, a small amount of air in the venous side of the circuit will be well tolerated, but large amounts of air that accumulate at the venous reservoir may predispose to systemic air embolization. In addition, if a second pump is used in the venous circuit, the perfusionist must be vigilant to keep the venous drainage and systemic flow balanced. If not, dramatic changes in the patient's intravascular volume may occur very quickly. Lastly, hemolysis may result from excessive negative pressures in the venous line [19, 20].

Arterial cannulas

A wide variety of arterial cannulas are available for clinical use. Differences in their materials and design facilitate their use in different arteries, both central and peripheral, during cannulation. The arterial cannula is typically the narrowest portion of the perfusion circuit. As a result, the arterial cannula is subject to relatively large pressure gradients across the cannula. As a general rule, the shorter the narrow segment of the arterial cannula, the lower the pressure gradient will be. As an example, a long, uniformly narrow cannula will be highly resistant to flow and there are few examples of this type of design. Ordinarily, arterial cannulas narrow only at or near their tip to minimize this problem. At the tip, the use of hard plastic or metal may be used to increase the inside diameter (ID) to outside diameter (OD) ratio and minimize the pressure gradient. Hemolysis and protein denaturation may occur with pressure gradients of greater than 100 mm Hg [21]. Regardless of the design of the arterial cannula, high-velocity jets of blood exiting the cannula and entering the cannulated artery may produce localized damage such as tearing, dislodgment of calcific plaque (producing circulating emboli), or arterial dissection. Devices such as the EMBOL-X Intraaortic Filtration System (EMBOL-X Inc., Mountain View, CA) have shown promise in the extraction of particulate debris at the arterial cannula tip, but the clinical utility of these devices is yet to be proved [22]. These devices are promising since cerebral macroembolism is thought to be a major determinant of neurologic injury after CPB [23–25].

Arterial cannulation

Arterial cannulation for cardiac surgery can be accomplished through a variety of arteries. In adult cardiac surgical procedures, the aorta is the most

common site for arterial cannulation, but other arteries such as the femoral artery or axillary artery may also be used.

Aortic cannulation

The aorta is easily exposed through the standard median sternotomy incision and is a *relatively* safe site for cannulation. Dislodgment and circulation of emboli from calcific plaque from the aorta is thought to be responsible for many of the neurological complications associated with cardiac surgery [23–25]. Embolization can be due to either direct manipulation of the aorta during cannulation or the effects of a high-velocity jet of blood striking the inner surface of the diseased aorta. Embolism of very small particles may produce no symptoms at all in many patients, but these small particles may be responsible for some of the neurocognitive changes encountered postoperatively in some patients [26–31]. Aortic cannulas with side holes, instead of end holes, near the tip may help to disperse blood as it enters the aorta and help to limit embolic injury [32].

Several techniques are available to help prevent inadvertent embolization. The surgeon should use manual palpation of the ascending aorta and exposed portion of the aortic arch and proximal great vessels to evaluate for the presence of calcific plaque. It is important to be sure that the planned sites for arterial cannulation, cardioplegia cannulation, aortic cross-clamping, and proximal anastomoses are free from significant disease. Unfortunately, manual palpation alone can underestimate the extent of atherosclerotic disease in these vessels [33–37]. With the introduction and increasingly widespread use of TEE during cardiac surgical procedures, this is another technique that can be used to assess the extent of atherosclerosis in the ascending aorta. Although TEE may not be able to image the mid-portion of the aortic arch completely, this technique can be used to assess the ascending and descending portions of the aorta [36–38]. More recently, epiaortic ultrasound has become the most sensitive method for the detection of significant atherosclerotic disease in the ascending aorta before cannulation [36, 37]. With this technique, an ultrasound probe in a sterile sheath is passed into the operative field. The pericardium is filled with saline and the probe is placed directly on the aorta to create cross-sectional or longitudinal images. When significant disease is discovered, the operative plan can be changed in response to the findings: (i) an alternative site for arterial cannulation such as the axillary artery or femoral artery may be selected, (ii) sites that are free of disease can be selected for cannulation, aortic cross-clamping, and siting of proximal anastomoses, (iii) for patients requiring only CABG, an off-pump approach might be selected, and (iv) a decision can be made in certain cases to replace the ascending aorta in addition to the originally planned procedure.

When aortic cannulation is performed, most surgeons place a single or two concentric purse-string sutures directly in the anterior surface of the ascending aorta. Often, the adventitia is cleared within the purse-string suture(s) before cannulation. The systemic blood pressure should be kept in the low

normal range during aortic cannulation to help prevent the complications of aortic tear or dissection. Intraluminal placement of the cannula is suggested by back-bleeding into the cannula and the presence of a pulsatile blood pressure in the arterial line. Back-bleeding into the cannula may also facilitate removal of small particulate debris dislodged at the cannulation site as well as small amounts of entrained air. The tip of the aortic cannula should be directed toward the central portion of the aortic arch.

A variety of complications are possible during or due to aortic cannulation. First, it may not be possible to introduce the cannula properly. This may be due to too small an opening, to fibrosis of the aortic wall, or to calcific plaque at the site of cannulation. It may be possible to insert the cannula tip into an intramural location; in this case, an improper cannulation may not be noticed until there is obstruction to blood flow and a high perfusion pressure is noted by the perfusionist when CPB is initiated. Too vigorous an introduction of the cannula may result in tearing at the cannulation site or to injury to the back wall of the aorta. Poor positioning of the tip of the cannula may result in "retrograde" cannulation, with the tip pointing toward (or even through) the aortic valve. Other undesirable locations for the cannula tip include the head vessels or in a position firmly against the aortic wall itself; these positions may be suggested by high line pressures when CPB is initiated. Intramural hematoma may occur at the site of cannulation and is treated by prompt incision of the adventitia. Antegrade aortic dissection during cannulation occurs in less than 0.1% of cases and is suggested by a sudden enlargement and bluish discoloration of the aorta, sudden bleeding from cannulation sites, and difficulties with venous return and arterial inflow [38–41]. Although this complication can be treated occasionally by suture plication of the ascending aorta, more often CPB must be reestablished via an alternative route (e.g., femoral artery) to facilitate repair or replacement of the ascending aorta.

Immediately after decannulation, any bleeding at the aortic cannulation site can usually be controlled by placement of additional sutures. Late complications after aortic cannulation may include recurrent hemorrhage or the development of a pseudoaneurysm [42].

Femoral artery cannulation

Femoral artery cannulation is used when the ascending aorta is not available for arterial cannulation (e.g., aneurysm or dissection of the ascending aorta, minimal access surgery with poor exposure of the ascending aorta). Although femoral cannulation can be accomplished percutaneously, more often the femoral artery is exposed surgically, necessitating an additional surgical incision. Complications related to femoral cannulation include direct injury to the femoral vessel, bleeding, dissection, formation of a pseudoaneurysm, formation of a lymphocele, nerve injury, retrograde dissection of the aorta [43, 44], and embolism (either air or calcific debris) to the distal extremity.

During CPB with femoral cannulation, the distal extremity may become ischemic. With prolonged ischemia, tissue necrosis and the development of

compartment syndrome in either the calf or thigh may occur [45]. As an alternative to direct cannulation, a graft (e.g., PTFE, Dacron) can be sutured end-to-side to the femoral artery to allow introduction of the arterial cannula while maintaining distal perfusion. Alternatively, a second, smaller caliber perfusion cannula can be placed in the femoral artery distal to the site of cannulation to provide distal perfusion to the extremity.

Femoral cannulation and subsequent "retrograde" perfusion may result in "retrograde" embolism if any calcific debris is dislodged from the femoral, iliac, or descending aortic vessels. TEE can be used to screen for the presence of atherosclerosis in the descending aorta and if there is severe disease (and especially, for cases in which there is loose or "hanging" debris), an alternative site for cannulation (e.g., axillary artery) should be selected.

Axillary artery cannulation

The axillary artery has recently been advocated for situations in which cannulation of the aorta or the femoral artery is not possible or desired [46, 47]. The right axillary artery is typically favored over the left. The axillary artery is less likely than either the aorta or femoral artery to be heavily involved with atherosclerosis. In addition, there is good collateralization around this artery, and if a separate incision is used for cannulation, wound healing is often better than for a groin incision. The axillary artery can be cannulated directly or through a small caliber graft that is attached to the axillary artery in end-to-side fashion.

Pump oxygenator

The two basic types of oxygenators in use today are the membrane oxygenator and the bubble oxygenator [48]. The membrane oxygenator is used almost universally worldwide, however. The "oxygenator" is responsible for both oxygenation and ventilation (e.g., CO_2 removal). For the typical microporous membranes (usually hollow fiber), there is direct contact between the blood and the membrane only at the outset of CPB. A thin protein coating then forms on the membrane quickly after the initiation of CPB and prevents direct contact between the blood and the membrane thereafter. Ventilation is controlled by the rate of gas flow and oxygenation is controlled by adjusting the oxygen fraction in the gas supplied to the oxygenator. There is a relatively high resistance to flow across the membrane, so blood must be pumped across the membrane before returning to the patient via the arterial line.

Compared to bubble oxygenators, the use of a membrane oxygenator is associated with less hemolysis [49]. Studies have shown that, regardless of the type of oxygenator, there is reduced red blood cell survival after CPB [50]. The membrane oxygenator may also be associated with reduced complement activation, granulocyte activation, and platelet activation [49–53]. Some, but not all, studies have also shown less cerebral microembolism with membrane than with bubble oxygenators [54, 55]. When an arterial filter is used, these differences are less pronounced, however. Recently, heparin-coated oxygenators

have become available and have been advocated because of potential reductions in the subsequent systemic inflammatory response [56, 57].

Bypass pump

A pump is placed in the perfusion circuit to provide forward flow of blood through the circuit and back to the patient. Two general types are available: roller pumps and centrifugal pumps [58]. Each has relative advantages and disadvantages as well as its own set of potential complications. Even if a centrifugal pump is used as the primary pump, roller pumps are typically used for delivery of cardioplegia and the operation of any cardiotomy or vent suction lines.

With the roller pump, a length of tubing is placed in a curved "raceway" that is adjacent to a set of rollers. Forward flow is generated as the rollers spin, compressing the tubing in the raceway. For a given pump and tubing type, the flow rate that is generated is proportional to the pump speed (in rpm). The degree of occlusiveness of the rollers against the tubing is important. Too much compression may promote hemolysis and too little compression may reduce the effective forward flow rate. The ideal degree of compression may occur when the rollers are adjusted to be just barely nonocclusive [19]. Other complications that are specific to the use of roller pumps include miscalibration [59] and the potential for fracture of the pump tubing. The roller pump is particularly susceptible to pumping large amounts of air into the arterial line if the venous reservoir is not monitored carefully and empties inadvertently. Spallation, the fragmentation and detachment of tubing particles, may also occur and an arterial line filter will limit subsequent embolization [60–62]. If there is inadvertent obstruction to outflow in the arterial line (e.g., from a clamp), pressure will build up in the arterial line until the tubing separates at a connector or the tubing ruptures.

The centrifugal pump has an impeller design and is totally nonocclusive. The resulting flow rate with a centrifugal pump is not only determined by the rotational rate of the pump, but is also affected by the afterload in both the circuit and the patient. When the pump is not rotating, blood can flow backward (e.g., from the patient) and exsanguination may occur if the arterial line is not clamped [63]. By the same mechanism, it is possible to draw air into the arterial side of the perfusion circuit at the cannulation site. In the event that the arterial line becomes occluded, the centrifugal pump, unlike the roller pump, will not generate high pressures and it is unlikely that the tubing would rupture. One purported benefit of the centrifugal pump over the roller pump is a reduced likelihood for air embolism. Although it is true that a large amount of air will "de-prime" the centrifugal pump (stopping it), smaller amounts of air may easily be pumped into the arterial line.

Heat exchanger

One or more heat exchangers may be placed in the perfusion circuit to warm or cool the patient's blood. The main heat exchanger is generally placed before

the oxygenator to prevent any release of microbubbles because of warming blood that has just been oxygenated. The hot or cold water source may come from the hospital's supply line or be part of a stand-alone unit. Malfunction of the heater–cooler during CPB will result in an inability to control the temperature of the patient's blood properly [64].

Cardiotomy suction

The use of cardiotomy suction during cardiac surgical procedures allows for even large amounts of blood to be evacuated from the operative field during the procedure [65]. This blood is typically returned to the perfusion circuit at the cardiotomy or venous reservoir by way of a defoaming chamber and a microfilter. These suction lines are typically regulated by a roller pump. The perfusionist must constantly monitor the speed of the roller pump because if the line or suction tip becomes occluded, high negative pressures may build up and promote hemolysis.

The use of cardiotomy and vent suction lines may result in hemolysis, gaseous or fat or other particulate microemboli, activation of coagulation and fibrinolysis, cellular aggregation, and platelet dysfunction [66–76]. Room air can be entrained into these suction lines and contribute to the formation of gaseous emboli and can produce additional shear stress that is detrimental to the blood elements. The detrimental effect of cardiotomy suction on the platelets is proportional to the amount of cardiotomy suction and the amount of entrained air [75, 76]. Hemolysis is due to negative pressure at the cardiotomy suction tip and the entrainment of air and is minimized if the largest possible cardiotomy suction tip is used with the minimum necessary suction and then, only when needed [77, 78].

Cell saver

The cell saver can be used in addition, or instead of, cardiotomy suction to scavenge blood from the operative field. With this technique, the scavenged cells are washed with saline and separated from the plasma by centrifugation. The cells can then be returned to the patient either intravenously or into the pump. In contrast to cardiotomy suction, the cell saver can be used, then, to filter out any particulates such as fat, air, and tissue before the blood is returned to the patient. The relative disadvantage is that there is loss of coagulation factors, platelets, and other plasma proteins that are lost during the centrifugation process. From a practical standpoint, the cell saver can be used instead of cardiotomy suction in operations in which there is little blood loss to the operative field (e.g., CABG). For operations in which larger volumes of bleeding are expected (e.g., redo operations, aortic surgery) and when venting is required, cell saver suction alone may not be practical. The cell saver can also be used at the conclusion of CPB to process any remaining blood in the venous reservoir before returning it to the patient.

Venting of the left heart

Suction lines, or "vents", can be used to decompress the left side of the heart during cardiac surgical procedures [65, 79]. Even during cardioplegic arrest, there will be return of bronchial, Thebesian vein, and coronary sinus blood flow to the right side of the heart that will, unless vented, make its way to the left side of the heart. In addition, aortic insufficiency may lead to filling of the left ventricle (through an incompetent aortic valve) during administration of antegrade cardioplegia. On the basis of experimental as well as clinical studies, venting this blood prevents distention of the ventricle that might increase myocardial oxygen demand and reduce subendocardial perfusion [80–82]. In addition, venting of the left side of the heart may help to prevent unwanted rewarming of the heart during cardioplegic arrest and facilitate the operative exposure. Nonetheless, there remains considerable variation in clinical practice and debate about the true benefits of routine venting of the left heart [83, 84].

Distention of the left side of the heart can be recognized visually, but the presence of cold saline or slush in the pericardium as well as the posterior location of the left ventricle may make recognition of left ventricular distention difficult. TEE can be used to monitor for distension of the left atrium and ventricle. An increase in the left atrial or pulmonary artery pressure (monitored by the pulmonary artery catheter) can also be an indication of left ventricular distention.

Several methods are available for left heart venting. An antegrade cardioplegia cannula inserted into the ascending aorta provides an opportunity for aortic root venting. Venting is not possible during administration of cardioplegia, however. In addition, if aortic insufficiency is present, it may be necessary to administer the antegrade cardioplegia intermittently to prevent left ventricular distention. Complications associated with the use of aortic root venting include potential injury to the aorta at the cannulation site (and even early or late aortic dissection) and introduction of air into the aorta if overzealous suction is applied to the root vent. A second option for left heart venting is direct venting of the left ventricle, with insertion of a vent catheter directly through the apex into the left ventricle. This technique is seldom used today because of the risk of bleeding, myocardial injury, and even late pseudoaneurysm formation. Insertion of vent catheters directly into the left atrium or into the pulmonary artery may have applications, but these methods may not be completely effective for venting the left ventricle. The most common method for LV venting is indirect, with insertion of a vent catheter through a pulmonary vein (usually the right superior) into the left atrium, and through the mitral valve into the LV.

Several complications have been associated with left heart venting [85]. Air can be introduced into the left side of the heart, either during insertion or removal of the vent catheter. The likelihood of this complication can be reduced if the heart is allowed to fill, at least partially, during insertion and removal of the LV vent catheter. It may also be useful to remove the LV vent catheter

while the pericardium is filled with saline (or blood) and the lungs are inflated to prevent aspiration of air into the left atrium. Excessive suction on the LV vent may cause introduction of air into the left heart around the purse-string suture or through open coronary arteries during the operative procedure [86]. It is important for the perfusionist to be vigilant for entrapment of the vent catheter tip and to prevent excessive suction. Mishaps with the LV vent line, in which positive pressure was applied to this line, have been reported. A one-way valve in the LV vent line will prevent the introduction of air. Whenever LV venting is used, there should be meticulous efforts for de-airing to avoid subsequent embolization of air that is entrapped in the pulmonary veins, left atrium, or left ventricle. TEE can be used to evaluate the effectiveness of de-airing maneuvers [87]. More recently, many surgeons have adopted the practice of "flooding" the field with CO_2, particularly during portions of an operation when the left side of the heart is open. When this technique is used, excessive CO_2 absorption may lead to hypercarbia and metabolic acidosis in rare cases [88]. Because it is more soluble, residual CO_2 in the heart is much less likely to cause difficulties with embolization.

Mechanical complications during CPB

Electrical failure

A variety of electrical mishaps may occur during CPB, but these problems rarely cause significant harm to the patient [89]. A total power failure will affect the CPB pump as well as its monitors. All perfusion pumps should have a hand crank available so that manual operation of the CPB pump can continue despite an electrical power failure. Many hospitals in the United States are equipped with emergency power generators in the event of a power failure, but it may take several minutes for a backup generator to come on line. More recently, operating rooms have been equipped with isolated electrical systems with a local backup power supply in the event that the main hospital power fails. Newer perfusion machines are often equipped with battery backup power units as a component. With all of these systems and safeguards, however, it is important to have regular safety checks and periodic review of emergency procedures.

Massive air embolism

Massive air embolism is a rare complication, occurring in less than 0.2% of cases, but the impact of this complication can be devastating [89]. Nearly 50% of affected patients die or suffer permanent neurologic damage [90]. In general, this term refers to embolism to the systemic, rather than the pulmonary circulation. Because of the "open" nature of the perfusion circuit, there are many potential sites for introduction of air, including the operative field, the perfusion circuit itself, or introduction of air inadvertently or iatrogenically through intravenous lines [91].

At the operative field, air can be introduced during the surgical procedure at a variety of stages. Before an aortic cross-clamp is applied, small amounts of air may be introduced inadvertently during aortic cannulation or insertion of antegrade cardioplegia delivery cannulas. Back-bleeding into the cannulas during these cannulations may help to prevent the introduction of air. If the left side of the heart is opened during the procedure, there is an obvious opportunity for air to be introduced and entrapped. The left atrium, left ventricle, and pulmonary veins are all sites where air can become entrapped. Rigorous de-airing maneuvers at the conclusion of the operative procedure are warranted and TEE can be used to evaluate the success of these maneuvers. Even when the left side of the heart is not opened (e.g., during CABG operations), air can be drawn in through openings in the coronary arteries if there is excessive venting at the aortic root or through a superior pulmonary vein.

There are many opportunities for introduction of air in the perfusion circuit [92]. Inadvertent emptying of the venous reservoir and pumping of air into the arterial side of the circuit may be the most common cause of massive air embolism [93, 94]. Modern perfusion setups typically include monitors and alarms to indicate a low level in the venous reservoir, but attention to this potential situation on the part of the perfusionist is probably the most important safeguard. When a roller pump is used as the primary pump, fracture of the tubing at the roller head may cause the introduction of air. In addition, any break in the arterial side of the circuit (e.g., fracture, open stopcock) may predispose to the introduction of air. Another potential source for introduction of air is cavitation that can occur at sites of high-velocity flow through restricted diameter tubing (e.g., at kinks, at sites of clamping).

Air embolism can be recognized at several stages during operation. Perhaps the most common stage where air embolism is suspected is during weaning from CPB. Introduction of air antegrade into the coronary arteries can produce temporary myocardial dysfunction that is recognized by regional ECG changes or regional changes in myocardial function by TEE. Raising the aortic root pressure, either pharmacologically or by partial manual occlusion of the distal aorta, may help to force air through the coronary arteries into the venous circulation. As an alternative, with the cross-clamp still applied, a large syringe can be used to inject blood under pressure directly into the aortic root to help pass intracoronary air into the venous circulation [95]. In addition, the administration of retrograde cardioplegia may help to force air from the coronary arteries into the aortic root, where it can be removed with an aortic root vent catheter [96]. The patient can be supported by continued CPB and this problem should resolve in several minutes.

If massive air embolism is recognized during operation, the source of the air must be determined quickly. CPB should be stopped immediately if the source of air is from the arterial side of the perfusion circuit. In this situation, the venous line should be clamped to prevent exsanguination. Air in the arterial line should be removed either by aspiration or by filling before CPB is

reinitiated. A variety of techniques are available to remove unwanted air from the other components of the perfusion circuit such as the oxygenator, centrifugal pump, and arterial filter [89]. Some authorities have recommended placing the patient in Trendelenburg position to allow air to flow back into the ascending aorta (for possible aspiration), but recent animal experiments have called this practice into question [97, 98]. If a large volume of air is suspected to have entered the arterial circulation, the use of a period of retrograde cerebral perfusion and profound systemic hypothermia may limit permanent neurologic injury [99–103]. Pharmacologic therapy may be useful during an episode of massive air embolism, but there is not much clinical data to guide the surgeon. Corticosteroids, anticonvulsants, barbiturates, and diuretics may be used to help limit neurological injury or the symptoms of that injury. One useful algorithm for the postoperative treatment of patients with massive air embolism is presented in Figure 4.2 [104]. When the operation is completed and the patient is sufficiently stable for transfer to a suitable facility, consideration should be given to additional treatment in a hyperbaric chamber [105–107].

Monitoring for CPB and related complications

The level of monitoring for an individual patient undergoing a cardiac surgical procedure will depend not only on the patient's characteristics (e.g., cardiac function, type of operation, other medical conditions), but also on institutional factors (e.g., availability of resources, technical expertise, program objectives, etc.). Typical monitoring may include arterial catheters, central venous catheters, pulmonary artery catheters, and TEE. Each of these monitoring techniques carries a small risk of complications.

Arterial catheters

Placement of an arterial catheter allows for continuous blood pressure monitoring and facilitates blood sampling for arterial blood gas determinations both during and after CPB. The radial artery is the most common site of cannulation, but the femoral and other arteries may also be used [108].

Before sterile insertion of the radial artery catheter, the overlying skin should be cleansed thoroughly. Injury to the artery can be avoided by a gentle insertion technique; the catheter should not be advanced forcefully. Selection of the contralateral radial artery for cannulation may be preferable to repeated cannulation attempts at the same site. The use of a topical antibiotic at the insertion site is controversial, but a sterile dressing should be applied. If a stopcock and extension tubing set are used, care should be taken to ensure that excess pressure is not placed on the stopcock against the patient's arm or hand because this may cause discomfort and skin necrosis.

Complications of radial artery cannulation may include infection, embolization, ischemia, and hematoma formation [109–111]. Cellulitis at the site of cannulation may occur in as many as 10% of patients, but documented bacteremia

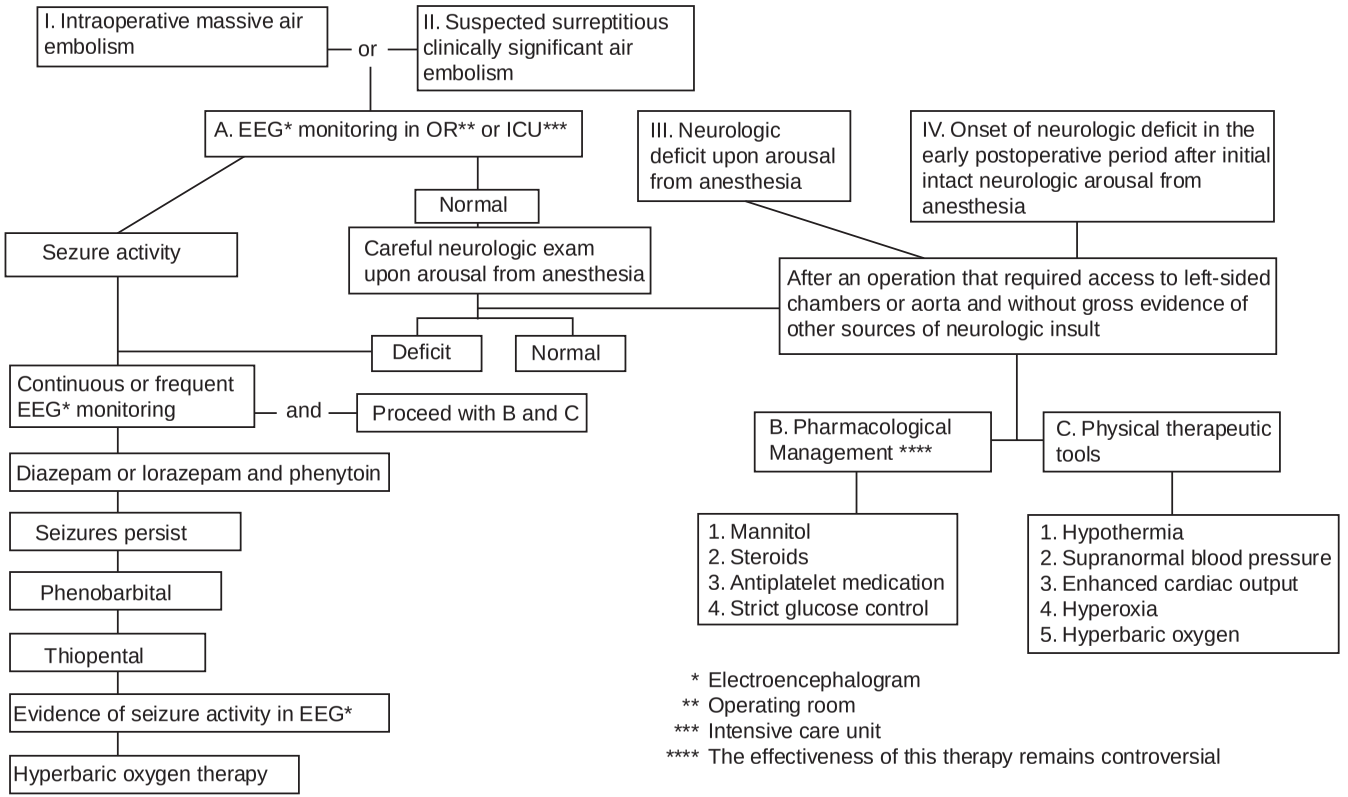

Figure 4.2 An algorithm for postoperative treatment of patients with air embolism. (*Source*: From Ref. [104], with permission from Elsevier.)

is rare [112, 113]. Ischemic complications are also uncommon. The Allen's test is often used to evaluate the integrity of the ulnar artery and palmar arch before radial artery cannulation, but this test is not completely reliable for predicting ischemic complications. Distal embolization may produce evidence of ischemia at the fingertips and thrombosis of the radial artery may occur in 1–2% of patients. Serious sequelae are uncommon because of collateral blood supply [112, 113]. Patients with poor peripheral blood flow, particularly in the setting of high-dose vasopressor therapy, are more prone to this complication. Removing the catheter is the treatment and the catheter should be removed as soon as an ischemic complication is suspected. Hematoma formation usually occurs with inadequate compression after a failed cannulation attempt or removal of a radial artery catheter, particularly in the setting of systemic anticoagulation. Other uncommon complications include necrosis of the skin overlying the insertion site, formation of an arterio–venous fistula or pseudoaneurysm, and median nerve neuropathy.

Femoral arterial cannulation is often used when the radial artery(ies) are not available (e.g., used for bypass conduits) [114]. Sterile technique should be used and a longer catheter may help to prevent inadvertent dislodgment. The femoral arterial catheter should be sutured to the skin and a sterile dressing should be applied. Potential complications include infection at the cannulation site, bacteremia, distal embolization, pseudoaneurysm, the formation of an arterio–venous fistula, and injury to the femoral nerve. Femoral arterial catheters or introducer sheaths (often placed at the time of cardiac catheterization) should be removed as early as possible to prevent complications and promote early mobilization of the patient [115, 116].

Central venous catheters

Central venous catheterization can be used for (i) intravenous access for the administration of medications, fluids, or blood products, (ii) monitoring the central venous pressure, and (iii) subsequent cannulation of the pulmonary artery with a Swan–Ganz catheter. The internal or external jugular and subclavian veins are used most commonly, but the femoral vein may also be used. The most common immediate complications of central venous catheterization include (i) inadvertent injury to the nearby artery, (ii) misplacement of the catheter, and (iii) pneumothorax [117–123].

Arterial puncture can often be recognized by the return of pulsatile blood when the syringe is removed from the large-bore introducer needle. If this occurs, the needle should be removed immediately. In the case of jugular insertion, the frequency of carotid arterial puncture is approximately 4%. If the jugular or femoral route is being used, pressure should be held at the cannulation site to help prevent hematoma formation. The usefulness of manual pressure to the subclavian artery and vein is controversial. Occasionally, arterial cannulation will not be recognized until after the catheter has been inserted. Arterial catheterization may be indicated by IV fluids that do not flow freely into the catheter, an arterial pressure tracing, or an "arterial" course of

the catheter on a subsequent chest radiograph (CXR). Once arterial catheterization has been discovered, the catheter should be removed and pressure should be held over the cannulation site. Unexplained blood loss or hemodynamic instability during a cardiac operation should prompt consideration of vascular injury from central venous catheterization and the ipsilateral pleural space should be inspected.

For catheters placed by the jugular or subclavian routes, the catheter tip should lie at the junction between the superior vena cava and the right atrium. A CXR immediately after operation should be used to document the correct position of the catheter tip and to evaluate for any unexpected hematoma or pleural effusion [124]. A variety of incorrect positions are possible: "doubled back" into the contralateral neck, distally in the subclavian vein, in the internal mammary vein, looped or coiled in the right atrium, in the inferior vena cava, across the chest into the contralateral subclavian vein, or abutting the SVC wall [125]. A mispositioned catheter may not necessarily be harmful to the patient, but we recommend removal and replacement of all mispositioned catheters. If the guide wire is inadvertently "lost" into the central circulation, urgent retrieval is indicated. In many cases, these guide wires can be retrieved by an interventional radiologist using an intravascular snare.

Depending on the route of central venous catheterization, pneumothorax occurs in approximately 1–4% of cases [117–119, 126]. Tension pneumothorax may be manifested by cardiopulmonary compromise or increasing airway pressures and can be treated by introduction of a large-bore needle or catheter through the second intercostal space, anteriorly. Pneumothorax is occasionally recognized after opening the chest and visualizing the air in the pleural space, an opening in the pleura serves to decompress the pneumothorax.

Late complications of central venous catheterization may not manifest until after the operation and, sometimes, not for hours to days. *Venous thrombosis* may occur, particularly in patients with large-bore, multilumen catheters that are left in place for long periods of time. This condition may manifest with unilateral upper extremity or neck swelling and discomfort. The diagnosis can be confirmed by ultrasound or venography. The catheter should be removed and consideration should be given to systemic anticoagulation. *Catheter-related infection* may be suggested by erythema or drainage at the insertion site, fever, leukocytosis, and documented bacteremia. When infection is suggested, the catheter should be removed and replaced at another site, if needed. Some authorities have recommended routine replacement of central venous catheters after several days to help prevent catheter-related infection, but there is no consensus [117, 127]. *Air embolism* may occur if a port or stopcock is left open or if a catheter is removed with the patient in the upright position [128]. As little as 5–10 cc of air may cause cardiac arrest. If air embolism occurs, the patient should be placed on the left side and the catheter should be aspirated to remove any air. Thoracotomy is occasionally indicated for removal of air directly from the pulmonary artery.

In some centers, multiple central venous catheters are used for monitoring in patients undergoing cardiac surgical procedures. By report, this practice is

associated with little additional risk of complication compared to single venous catheterization [129].

Pulmonary artery catheters

A pulmonary artery (e.g., Swan–Ganz) catheter is used to provide information about the central venous, pulmonary artery, and pulmonary artery wedge pressures and to allow continuous or "on-demand" measurement of the cardiac output and mixed venous oxygen saturation. Postoperatively, the pulmonary artery catheter can be used to provide information about the patient's intravascular volume status, aid in the treatment of heart failure, and facilitate temporary pacemaking (through a pacing port). Because the pulmonary artery catheter is typically placed through an introducer sheath in a central vein, pulmonary artery catheterization is associated with many of the same complications as central venous catheterization (see above).

Serious complications related to the use of a pulmonary artery catheter for cardiac surgery are uncommon [130]. During insertion of the pulmonary artery catheter, transient or sustained arrhythmias may occur and should be treated by prompt advancement or withdrawal of the catheter. During any withdrawal of the catheter, the balloon should be deflated to prevent injury to the pulmonary or tricuspid valves. Persistent arrhythmias should prompt consideration for the administration of an antiarrhythmic medication such as lidocaine, but arrhythmias due to mechanical irritation of the catheter may be resistant to these medications [131]. Heart block may develop or may worsen, especially for patients with preexisting fascicular block. Perforation or injury to the tricuspid valve [132], pulmonary valve [133], or ventricle during insertion is rare. A pulmonary artery catheter that becomes knotted can usually be removed nonsurgically, often by the interventional radiologist [134].

Rupture of the pulmonary artery is the most serious complication of pulmonary artery catheterization and carries a substantial mortality rate [130, 135–143]. Proper care of the pulmonary catheter aimed at preventing this complication requires frequent checking to make certain that the catheter tip does not remain in the "wedged" position. Movement during the cardiac surgical procedure is common and the anesthesiologist should be vigilant for this possibility. Pulmonary artery rupture is a potentially life-threatening complication that may produce localized or uncontrolled hemorrhage and quick deterioration of the hemodynamic and respiratory status. If hemoptysis suggests pulmonary artery rupture before the cardiac surgical procedure has begun, several measures may help temporize the situation. First, medications that affect clotting (e.g., heparin, Coumadin, aspirin) should be stopped, if possible, and alterations in the patient's clotting profile should be corrected with administration of vitamin K or fresh frozen plasma. Intubation and mechanical ventilation may be required. A thoracostomy tube should be inserted to drain any blood from the affected pleural space. Bronchoscopy may be helpful to determine an exact site of bleeding and can be used to insert a balloon-tipped catheter to isolate the affected pulmonary segment. Persistent bleeding should prompt exploration, either through a thoracotomy or

median sternotomy approach. A segmentectomy or lobectomy is used to control the bleeding. In this circumstance, cardiac operation is deferred, if possible.

Pulmonary rupture may manifest during the cardiac operation, usually at the conclusion of CPB, or later in the ICU. The principles of treatment outlined above apply in these situations as well.

TEE

TEE is a common diagnostic procedure outside of the operating room and is thought to carry little risk to the patient. In large series of TEE in the general cardiology population, the frequency of serious complications is less than 0.2% [144, 145]. The ultrasound probe and unit should be well maintained to prevent thermal or electrical injury to the patient and the probe should be cleaned properly to prevent disease transmission between patients.

Intraoperative TEE is used commonly today as a monitoring tool in cardiac surgery, particularly in those patients undergoing valve procedures, aortic procedures, and correction of congenital defects. Intraoperative TEE provides information about the cardiac anatomy and function that can help to determine the most appropriate surgical procedure (e.g., valve repair vs. replacement), facilitate weaning from CPB, and assess the immediate results of operation. In a large series of intraoperative TEE, the morbidity rate was 0.2% and the reported mortality rate attributable to TEE was 0% [146].

The most frequent complication of intraoperative TEE is transient odynophagia [146]. Swallowing dysfunction has been reported in up to 4% of patients after operations in which intraoperative TEE was used [147]. Proper care should be exercised during insertion of the TEE probe to prevent dental injury or dislodgment of the endotracheal tube [146]. Upper gastrointestinal bleeding may occur after intraoperative TEE, but this may be due not only to mechanical irritation by the TEE probe but also to preexisting conditions of the esophagus or stomach [146]. The most serious complication associated with intraoperative TEE is gastrointestinal tract perforation. This may occur in the oropharynx [148], hypopharynx [149], esophagus [146, 150, 151], or stomach. Some authorities have suggested that a preoperative history of dysphagia is a risk factor for perforation [149]. The treatment of patients with gastrointestinal perforation should focus on localization of the site of perforation, administration of antibiotics, and, in many cases, operative repair. This complication is associated with substantial morbidity and mortality risk for the patient [146, 150–152].

Anticoagulation for CPB and related complications

Anticoagulation for CPB

Some degree of anticoagulation is required during CPB to prevent coagulation within the pump circuit and its components. Although heparin is the most common agent used for anticoagulation in conjunction with CPB, other

anticoagulants may be useful in special circumstances. The surgeon, perfusionist, and anesthesiologist should be aware of the potentially adverse effects that are associated with each of these anticoagulants.

Heparin is the most common anticoagulant used for CPB because this agent is effective, reversible, well tolerated, and inexpensive [153]. Unfractionated heparin is a mixture of mast cell polysaccharides (1000–50 000 d) that produces its anticoagulant effect by potentiating the activity of antithrombin III (ATIII) and inhibiting thrombin directly by binding to cofactor II. There is substantial interpatient variability in the clinical effects of a fixed dose of heparin, however. In addition, acute reactions such as anaphylaxis, pulmonary edema, and disseminated intravascular coagulation (DIC) may occur rarely after administration of heparin.

For clinical applications other than anticoagulation for CPB, the most common complication following heparin administration is bleeding. In the setting of CPB, however, anticoagulation is essential regardless of the risk of any potential excess bleeding. During cardiac surgery, bleeding into the operative field does not usually pose a problem because of the availability of cell saver or cardiotomy suction. Excess administration of heparin, however, may produce fibrinolysis and unwanted platelet activation. Insufficient anticoagulation during CPB may result in consumption of coagulation factors.

Historically, heparin administration in preparation for CPB was guided empirically. Today, the appropriate dose of heparin can be monitored before and during CPB. The initial dosage is usually 200–400 U/kg, with maintenance doses (administered intermittently during CPB) of 50–100 U/kg. In addition, 10 000–20 000 U are typically placed in the bypass pump before the institution of CPB.

Heparin resistance

Heparin resistance refers to the circumstance in which a patient receives the standard dose of heparin before CPB but does not become fully anticoagulated. Several etiologies are possible, including congenital antithrombin III (ATIII) deficiency, acquired ATIII deficiency, thrombocytosis, pregnancy, sepsis, hypercoagulable states, and coagulopathic processes [154–158]. A deficiency of ATIII is the most common cause and can be treated with administration of fresh frozen plasma or recombinant ATIII [157].

Heparin-induced thrombocytopenia

Heparin-induced thrombocytopenia (HIT) occurs in up to 10% of patients treated with heparin [159–163] and has been documented in 1–5% of surgical patients [159]. This condition may manifest after exposure to either unfractionated or low molecular weight heparin preparations. The relatively high incidence of HIT in surgical patients has been attributed, in part, to the widespread use of heparin for a variety of indications and a high prevalence of heparin-associated antibodies in patients who are referred for cardiac surgery [159].

Two forms of HIT have been described [160]. Type I HIT is due to platelet aggregation and is associated with mild thrombocytopenia (never less than 100×10^9/L) [160]. For patients with type I HIT, the thrombocytopenia develops within a few days of heparin exposure but resolves without specific treatment. Patients are often asymptomatic and the risk of serious associated morbidity is low. Type II HIT is immunologically mediated, with development of heparin-associated antiplatelet antibodies that promote platelet activation [160, 161]. The IgG, IgA, or IgM antibodies are directed against the complex of heparin and platelet factor 4 (H-PF4) [161]. For patients with type II HIT, the thrombocytopenia often develops 5–14 days after heparin exposure, and the platelet count is often well below 100×10^9/L [160].

The more serious condition of heparin-induced thrombocytopenia and thrombosis (HITT) occurs in a subset of patients with HIT, and in 10% of these individuals, there is significant end-organ injury due to thrombosis [159]. A variety of vascular complications may occur, including cerebral infarction, mesenteric infarction, myocardial infarction, bypass graft occlusion, and limb ischemia. Amputation may be needed in as many as 25% of patients with affected limbs. The mortality rate approaches 30% [159].

There should be a high index of suspicion for the diagnoses of HIT and HITT. The diagnosis of HIT is suggested by a fall in the platelet count of more than 50% or an absolute platelet count less than 100×10^9/L [159]. When this diagnosis is suspected, heparin should be withheld in all of its forms, the platelet count should be measured daily, and the patient should be monitored closely for the development of thrombotic complications. A variety of laboratory tests are available to establish the diagnosis of HIT, including platelet aggregometry, the serotonin release assay (SRA), flow cytometric assays, and enzyme-linked immunosorbent assay (ELISA) to measure anti-H-PF4 antibody titers [161]. Each of these tests has relative advantages and disadvantages and may not be available in all institutions. Because of slow turnaround time for these tests, treatment should be instituted promptly while awaiting the results of the laboratory test(s).

The primary treatment for patients with HIT is withdrawal of heparin and anticoagulation with another agent that reduces thrombin generation [162]. Agents that may be useful in this situation include danaparoid, ancrod, recombinant hirudin, and argatroban. Arterial thrombotic complications should be treated expeditiously.

Alternatives to heparin

Alternatives to heparin for anticoagulation may be useful for patients with a known heparin allergy, protamine allergy, or history of HIT [163]. For patients with a history of HIT, a delay in surgery may allow time for antiplatelet antibodies to fall to an unmeasurable level. Unfortunately, this does not necessarily preclude the development of recurrent HIT [163]. Another useful strategy may be preoperative plasmapheresis to remove circulating antiplatelet antibodies [164]. A variety of anticoagulants may be useful alternatives to heparin

in certain circumstances: warfarin, low molecular weight dextran, low molecular weight heparin, heparanoids (e.g., orgaran), ancrod, antithrombin agents (e.g., hirudin, argatroban), and prostacyclins [163, 165–167].

Monitoring of anticoagulation for CPB

Historically, heparin dosing was accomplished empirically, with a fixed dosage based on the patient's weight. In most centers today, however, an initial dose of heparin is administered and then the activated clotting time (ACT) or heparin levels are monitored periodically to (i) ensure adequate anticoagulation *before* the institution of CPB, (ii) assess the need for additional doses of heparin *during* CPB, and (iii) assess the effectiveness of reversal of heparinization *after* CPB.

Reversal of anticoagulation

At the conclusion of CPB, the effects of heparin are typically reversed with administration of protamine. Calculation of an appropriate dose of protamine is important because incomplete reversal of the heparin results from too little protamine, and excessive protamine administration may lead to increased platelet dysfunction, increased postoperative bleeding, and increased transfusion requirements [153]. Individual patient factors (e.g., sensitivity to protamine, metabolism of heparin) as well as operation-related factors (e.g., degree and duration of hypothermia) will influence the appropriate dose of protamine for a given patient [168].

Several techniques are available to calculate the appropriate dose of protamine. In the simplest technique, a fixed dose of protamine can be administered per amount of heparin that is administered. This calculation can be based either on the initial heparin dose or on the total amount of heparin administered during the operation [169]. A variety of approaches have been described, with administration of as little as 1 mg to as much as 5 mg of protamine for every 1 mg of heparin administered. A second method of calculating the appropriate protamine dose is by use of heparin dose–response curves that are based on the ACT before and during CPB [170]. This curve can be used at the conclusion of CPB to estimate an appropriate dose of protamine. This approach has been reported to reduce the amount of protamine used compared to the fixed-dose approach [169,171]. There are potential disadvantages to the heparin dose–response method, however. In particular, the heparin dose–response curve is actually nonlinear and this results in inaccuracies at either very low or very high levels of anticoagulation [169, 172–174]. The last method for calculation of the appropriate protamine dose is based on measurement of heparin concentrations directly [168, 175, 176]. Protamine titration using measured heparin concentrations may reduce the amount of protamine used by as much as 30–40% compared to the heparin dose–response curve method [153, 177].

Serious adverse reactions may occur with protamine administration [178, 179]. Risk factors include pulmonary hypertension, previous exposure to

protamine or protamine-containing insulin preparations, previous vasectomy, and fish allergies [180]. Some authorities have advocated administration of protamine on the left side of the circulation (e.g., into the aorta) to prevent pulmonary exposure to heparin–protamine complexes and to reduce the chance of pulmonary histamine release, but the results from clinical studies have been conflicting [181, 182].

Protamine reactions are usually described in three categories: type I, with transient hypotension; type II, with anaphylaxis; and type III, with pulmonary vasoconstriction [183, 184]. The *type I protamine reaction* is mediated by release of histamine from mast cells and basophils. This effect is more pronounced with rapid injection, so it is recommended that protamine be administered over 5–10 minutes, or longer [180, 185, 186]. Pretreatment with histamine receptor antagonists may reduce the effect but not eliminate the possibility of a type I reaction [187]. Histamine release produces reductions in the systemic arterial pressure and the central venous pressures. There will often be a reduction in the cardiac output, but this may be due simply to decreased preload [188, 189]. Animal studies have suggested a direct negative effect of protamine on myocardial contractility, but the evidence is not convincing in humans [189–191].

The classic *type II protamine reaction* is mediated by IgE on the surface of mast cells that interacts with protamine and causes degranulation. The symptoms may include rash, bronchospasm, edema, stridor, hypotension, and cardiovascular collapse. Patients at increased risk for this type of reaction include those with previous exposure to protamine or protamine-containing insulin preparations (e.g., NPH or protamine–zinc insulin), previous vasectomy, or fish allergies. Several tests are available to evaluate the patient for potential protamine allergy, including intradermal skin testing [180, 192]; in vitro whole blood leukocyte histamine release [182, 193]; and radioallergosorbent testing for serum antiprotamine IgE [180, 193, 194]. For most patients undergoing cardiac surgical procedures, however, these tests are not practical. Less commonly, type II anaphylactoid reactions are mediated by the classic complement pathway, in which protamine–heparin complexes cause release of C3a, C5a, and other vasoactive mediators, producing anaphylaxis d [195, 196].

In the *type III protamine reaction*, patients develop acute pulmonary hypertension, decreased left atrial pressure, right ventricular failure, and systemic hypotension [179, 180]. It is not clear whether the rate of protamine administration affects the likelihood of a type III reaction [183, 197]. The reaction may be transient or prolonged and may necessitate reinstitution of CPB. Readministration of protamine in a given patient may or may not result in the same reaction again. Although the mechanism of the type III reaction is not completely understood, it is most likely mediated by complement when protamine–heparin complexes result in release of vasoactive substances (e.g., oxygen free radicals, thromboxane A_2) [198–202].

There are several alternatives to protamine for the reversal of the effects of heparin, but none enjoy much clinical use. Hexadimethrine neutralizes heparin with the same mechanism as protamine and with less effect on the systemic hemodynamics [203, 204]. Unfortunately, this agent also produces direct lung injury and can cause a clinical syndrome of noncardiogenic pulmonary edema [205]. Moreover, this agent may produce platelet aggregation and renal failure [206, 207]. Because of these side effects, this agent is not currently clinically available. A second alternative is the use of a cellulose filter that contains immobilized protamine [208, 209]. This filter can be placed in the arterial line just before the termination of CPB. Several passes of blood through the circuit may be needed for effective neutralization of heparin, however, and this may result in fibrin-clot deposition at the filter. A third alternative to protamine is heparinase [210–212]. In animal studies, a heparinase-bonded filter has been shown to neutralize heparin effectively with two to three passes of the blood through the filter. A fourth alternative to protamine is platelet factor 4, a protein released from platelets with a highly specific heparin neutralizing property [213–217]. In animal models, platelet factor 4 has been shown to neutralize heparin effectively, with no effect on the platelet count, leukocyte count, or complement levels.

Residual circulating heparin may be present even after protamine administration if an insufficient amount of protamine is used or if there is subsequent release of heparin from heparin–protamine complexes, heparin-binding proteins, or from other sites [153]. The term *heparin rebound* is used to describe the situation in which there is recurrent heparin activity after complete neutralization of heparin. Persistent circulating heparin, regardless of the cause, may lead to an increase in bleeding after CPB [153].

CPB and bleeding

Cardiac surgical patients are particularly susceptible to postoperative mediastinal bleeding. The incidence of severe bleeding after CPB depends on the definition, but as many as 5–7% of patients may experience bleeding of greater than 2 L during the first 24 hours after operation [218]. In recently reported large series of adult cardiac surgery patients, as many as 3–5% of patients require reexploration of the chest because of excessive postoperative bleeding [218, 220]. The need for reexploration of the chest after a cardiac surgical procedure is associated with substantial morbidity and mortality [221]. In one large series, reexploration was associated with a twofold increase in operative mortality as well as a significantly increased incidence of renal failure, adult respiratory distress syndrome (ARDS), prolonged mechanical ventilation, sepsis, and atrial arrhythmias [219]. In addition, the transfusion of blood products because of excessive bleeding is associated with a variety of potentially adverse events, including blood-borne disease transmission (e.g., hepatitis, HIV), increased incidence of wound infection, and transfusion reactions [221].

Aprotinin and Amicar

Fibrinolysis ordinarily prevents or limits propagation of intravascular thrombosis. Although the mechanism is not entirely clear, there is typically increased fibrinolytic activity during cardiac surgery [222]. Two antifibrinolytic agents are currently available to help limit fibrinolytic activity during CPB and to help reduce postoperative bleeding: tranexamic acid, epsilon-aminocaproic acid (ε-aminocaproic acid, EACA, Amicar). Of these agents, ε-aminocaproic acid (Amicar) has been shown to reduce antifibrinolytic activity during CPB and to reduce postoperative bleeding and transfusion requirements, particularly among patients undergoing "redo" operations [222]. One agent that was used in the past but is no longer on the market is aprotinin (Trasylol) [223–225]. Patients who received aprotinin had a higher mortality rate and larger increases in serum creatinine levels than those who received aminocaproic acid or no antifibrinolytic agent [226, 227]. Postoperative urinary NGAL (neutrophil gelatinase associated lipocalin) is a very sensitive marker for renal injury. Postoperative urinary NGAL is increased in cardiac surgical patients receiving aprotinin compared to patients receiving other antifibrinolytic agents. The rise of urinary NGAL may be due to aprotinin blocking the uptake of NGAL by megalin/gp330 receptors in proximal tubules [228].

Blood conservation techniques

Although blood product transfusion is generally safe, transfusion can be associated with viral or bacterial transmission [229] (Table 4.1), isoimmunization, potentially increased incidence of postoperative wound infection [230–232], and increased cost. Because of these potential risks as well as a limited supply of banked blood products, there is considerable impetus to avoid transfusion whenever possible, and today transfusion can be avoided in many cardiac surgery patients. A variety of techniques that can be applied before, during, and after operation can be used to help avoid blood product transfusion in patients undergoing cardiac surgery procedures (Table 4.2).

Preoperative techniques

Although the technique may be available to only a minority of cardiac surgery patients, autologous red blood cell predonation can be used to limit the need for allogeneic transfusion during and after operations of many types [233–235]. Factors that may limit the use of this technique in cardiac surgery patients include (i) insufficient lead time, (ii) preoperative anemia, and (iii) cardiac instability. In addition, autologous predonation is more expensive than allogeneic transfusion [236]. When 2 units of red blood cells are harvested over a 2–3-week period, the preoperative hemoglobin typically falls by approximately 2 g/dL. Even for patients who are anticipating cardiac surgery, however, this practice is generally safe and well tolerated [237, 238]. Erythropoetin has been shown to be useful, alone or in combination with iron, to

Table 4.1 Estimated risk of infectious agent transmission.

Variable	*Estimate*
Probability of infection (per allogeneic unit)	
Hepatitis C virus	0.0003
Hepatitis B virus	0.000005
HIV	0.0000067
HTLV-I and HTLV-II	0.000017
Probability of disease[a]	
Hepatitis C virus	
Persistent hepatitis	0.28
Active hepatitis	0.12
Cirrhosis	0.10
Fulminant hepatitis	0.01
Hepatitis B virus	
Carrier status	0.04
Persistent hepatitis	0.02
Active hepatitis	0.01
Cirrhosis or cancer	0.01
HIV	
AIDS	1.0
HTLV-I and HTLV-II	
ATL or HAM	0.04
Quality adjustments for various health states	
Persistent hepatitis	0.99
Active hepatitis	0.90
Cirrhosis or cancer	0.90
Fulminant hepatitis	0
HIV infection	0.75
AIDS	0.50
ATL or HAM	0.90

AIDS, acquired immunodeficiency syndrome; HAM, HTLV-associated myelopathy; HIV, human immunodeficiency virus; HTLV, human T-lymphocyte virus.
[a]*Source*: From Ref. [229], with permission. Copyright 1995 Massachusetts Medical Society.

improve the hematocrit in anemic patients before cardiac surgery and may improve the yield of autologous predonation in some patients [239–241].

Intraoperative techniques

A variety of intraoperative techniques are available to help reduce the need for allogeneic blood transfusion. The importance of rigorous surgical technique to limit bleeding during the operation should be emphasized. In contrast to the historical use of a whole blood prime, the CPB circuit today is typically primed with an acellular, or asanguinous, solution. Relative degrees of anemia during CPB, particularly at hypothermic temperatures, are well tolerated. Cell saving or pump suction (cardiotomy suction) devices are used during the operation to scavenge any shed blood. Any residual blood in the CPB pump is returned

Table 4.2 Techniques for reducing blood product transfusion in cardiac patients.

Perioperative
Autologous predonation of whole blood, red blood cells, FFP, platelets
Erythropoeitin
Intraoperative
Institutional program of guidelines for blood product transfusion
Rigorous surgical technique
Pre-CPB isovolemic hemodilution
Pre-CPB pheresis of platelets and FFP
Pheresis of FFP and platelets
Nonsanguinous prime
Whole blood collection at CPB onset
Retransfusion of pump blood
Cell saver or ultrafiltration of pump blood
Drug therapy
Antifibrinolytic agents
DDAVP
Postoperative
Institutional program of guidelines for allogeneic blood product administration
Shed mediastinal blood transfusion

Source: From Ref. [163], p. 443, with permission.
CPB, cardiopulmonary bypass; FFP, fresh frozen plasma.

to the patient using the cell saver, ultrafiltration, or simply as unprocessed blood. Each of these techniques has its relative advantages and disadvantages.

Preoperative harvesting of platelet-rich plasma (PRP) can be used to limit the exposure of platelets to CPB and is usually performed in the operating room before the initiation of CPB. Whole blood is collected, spun in a centrifuge to separate the PRP from the cells, and the blood is readministered to the patient. This process is repeated until a sufficient volume of PRP has been obtained. Using this technique, approximately 9–30% of the circulating platelets can be harvested and stored safely for 2–3 hours. The inability to harvest an adequate volume of platelets may currently limit the utility of this technique, but improvements in equipment and techniques may increase the yield of the harvest. Studies of intraoperative transfusion of PRP to reduce the need for postoperative allogeneic transfusion have produced mixed results [242–245].

Acute normovolemic hemodilution refers to the withdrawal of whole blood from the patient and replacement with crystalloid or colloid, usually before the initiation of CPB. Like harvesting of PRP, this technique protects blood elements from the deleterious effects of CPB. The withdrawal of blood can be accomplished either through a central venous catheter before heparinization (using citrate storage bags) or through the venous line of the CPB pump after heparinization. The volume of blood that can be withdrawn safely depends on the patient's body size and preoperative hemoglobin level, but in a typical patient approximately 1000 mL of blood can be withdrawn. This technique

appears to be safe and well tolerated in many patients and its efficacy in terms of reduction in allogeneic transfusion has been documented in several studies [246, 247]. Proponents point to a higher platelet count after CPB as the mechanism for reduced bleeding and transfusion requirement [248, 249].

Postoperative techniques

Institutional guidelines or "triggers" for blood product transfusion may limit unnecessary transfusion postoperatively. As an example, a "trigger" point hematocrit of 24% in the early postoperative period might prompt automatic transfusion of 2 units of red blood cells. This practice carries the advantage that transfusion happens automatically at predetermined "trigger" points. Unfortunately, though, automatic transfusion may not always be indicated for an individual patient.

Autotransfusion of shed mediastinal blood in the early postoperative period has been advocated as another technique to reduce the need for postoperative transfusion. Most [250–252] but not all studies [253–255] have shown this technique to be effective, but despite years of clinical use, there is still controversy regarding the safety of this technique. Potential complications with autotransfusion of shed mediastinal blood include altered coagulation [256], systemic fibrinolysis [257], and bacterial contamination [258].

Pathophysiologic consequences of CPB

The use of CPB produces pathophysiologic effects in nearly all of the body's organ systems. Although these effects might not be considered *complications* in the classic sense, they are a necessary by-product of CPB and lead to much of the morbidity associated with its use. A complete discussion of these pathophysiologic effects is beyond the scope of this chapter; the reader is referred to other sources for additional information [6, 259]. For the purpose of this chapter, we confine our discussion to the effects of CPB generated at the blood–surface interface; the consequences of hypothermia, which is often used in conjunction with CPB; the metabolic consequences of CPB; the effects of CPB on the lungs; the effects of CPB on the kidneys; and the neurological effects of CPB.

Consequences of the blood–surface interface

Ordinarily, the blood and plasma come into contact only with endothelial lined vessels. During cardiac surgical procedures with the use of CPB, however, the blood and plasma are exposed to a variety of foreign surfaces, including not only the components of the perfusion circuit but also the exposed tissues in the open surgical wound. As a result of this contact at the blood–surface interface, a host of specific reactions are initiated that result in a *systemic* response to CPB [260].

Almost immediately after contact with a nonendothelial surface, plasma proteins are adsorbed onto that surface, producing a monolayer of many

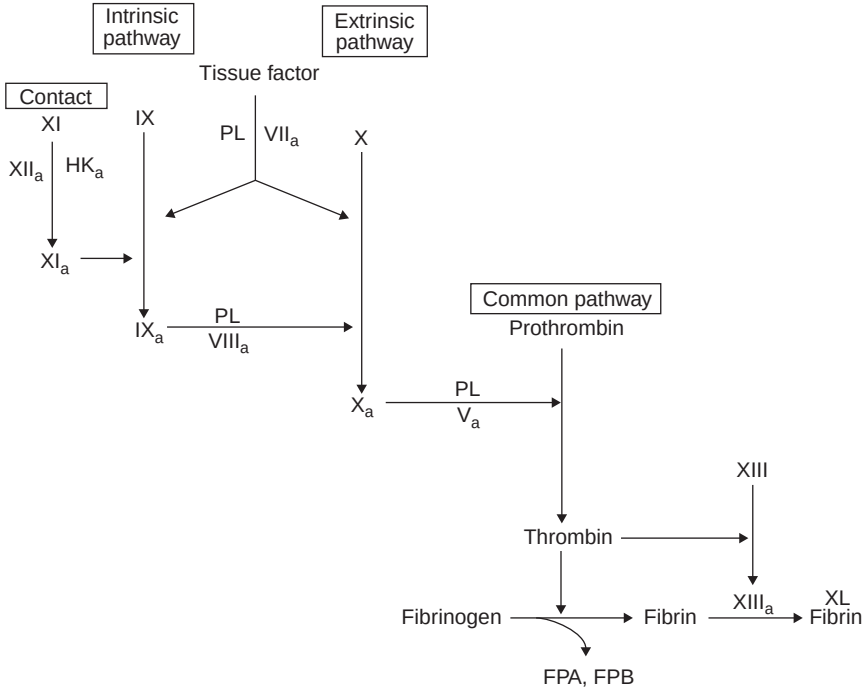

Figure 4.3 Complement pathways. (*Source*: From Ref. [265], with permission from LWW.)

different proteins [261, 262]. Fibrinogen is among the most important of the plasma proteins that is adsorbed [263, 264]. The type and relative mix of proteins will be determined by the particular nonendothelial surface involved.

For purposes of this discussion, we will discuss the resulting activation of the contact, intrinsic, and extrinsic coagulation pathways, fibrinolysis, and complement. We will also discuss the important effects on the platelets, endothelial cells, neutrophils, monocytes, and lymphocytes.

Contact activation system

The adsorption of factor XII (Hageman factor) onto a nonendothelial surface begins a cascade in the contact system pathway (Figure 4.3) [265]. In the presence of prekallikrein and high molecular weight kininogen (HMWK), the active proteases factor XIIa and XIIf are produced [266, 267]. In the presence of kallikrein and HMWK, factor XIIa activates factor XI to XIa, which initiates the intrinsic coagulation pathway, leading eventually to the formation of thrombin. Kallikrein and factor XIIa are both direct agonists for neutrophils.

Intrinsic coagulation pathway

The extrinsic coagulation pathway may be more important in the systemic response to CPB, but there is evidence that activation of the intrinsic coagulation

pathway also plays a role [268]. The complex of factor VIIIa, factor IXa, and phospholipids (PLs) binds to factor X and leads to the production of factor Xa, the entry into the common coagulation pathway.

Extrinsic coagulation pathway

Under ordinary circumstances, tissue factor is a membrane-bound protein that is not exposed to the blood. Activated monocytes and endothelial cells also express tissue factor [269, 270]. During CPB, tissue factor acts with activated factor VIIa and PL to promote activation of both factor IX to IXa and factor X to Xa, the entry into the common coagulation pathway. As such, factor Xa is produced by both the intrinsic and extrinsic coagulation pathways. The intrinsic coagulation pathway is activated primarily in the perfusion circuit and the extrinsic coagulation pathway is activated primarily in the surgical wound. The result of both coagulation pathways is the production of the circulating protease, thrombin.

Fibrinolysis

One of the effects of circulating thrombin is the activation of endothelial cells, leading to the release of tissue plasminogen activator (tPA), which then binds to fibrin. The combination of tPA, fibrin, and plasminogen cleaves plasminogen to plasmin. Plasmin then cleaves fibrin.

Complement

Both the classic and alternative complement pathways are activated during CPB (Figure 4.3). In the perfusion circuit, the blood–surface contact leads to activation of the classic pathway via C1, C2, and C4 to form C3 convertase that cleaves C3 into C3a and C3b. The alternate pathway, through factors B and D, also leads to production of C3b and may be the more important pathway during CPB [195]. The classic pathway is also activated at the termination of CPB when protamine is administered and heparin–protamine complexes are formed [271].

C3b then cleaves C5 into C5a and C5b. C5b leads to production of the terminal complement complex (TCC) by binding with C6, C7, C8, and C9. TCC interacts with cell membranes, leading to lysis of cells. In addition, TCC also leads to increased thrombin formation [272]. The released factors C3a, C4a, and C5a are vasoactive. C5a is a major neutrophil agonist [273, 274].

Platelets

The circulating platelets are subject to a variety of adverse influences during CPB. Perhaps the first noticeable effect on the platelets is a reduction in their circulating numbers because of dilution with the pump prime volume. Heparin inhibits platelet binding to von Willebrand's factor and increases the bleeding time [275, 276]. Heparin leads to increased sensitivity of the platelet to circulating agonists, including thrombin [277], C5b [272], plasmin [278, 279],

cathepsin G, serotonin, and epinephrine, among others. All of these influences contribute to platelet loss and dysfunction.

The numbers of circulating platelets are also reduced by platelet–platelet adhesion and aggregation. Activated platelets express a variety of cell surface glycoproteins and receptors that promote aggregation [280–282]. In addition to platelet–platelet aggregation, activated platelets also form aggregates with monocytes and neutrophils [280, 283].

A subset of the activated platelets will produce and release a variety of substances, including thromboxane A_2 [284], platelet factor 4, β-thromboglobulin [285], P-selectin [280], serotonin, adenosine diphosphate (ADP), adenosine triphosphate (ATP), calcium, mitogens, acid hydrolases [286], and neutral proteases.

Although the effect will depend on many factors, both with respect to the patient and the surgical procedure, the circulating platelet count typically falls by 30–50% during CPB [53, 287]. In addition to intact platelets, there are often platelet fragments in the circulation after the termination of CPB [288]. The overall platelet function is reduced and there is typically a prolongation of the measured bleeding time after CPB [53].

Endothelial cells

During CPB, endothelial cells are activated by thrombin, C5a, and a variety of cytokines (e.g., interleukin-1 [IL-1], tumor necrosis factor [TNF]) [289–291].

Neutrophils

The neutrophils are responsible for much of the systemic inflammatory response after CPB. These cells are strongly activated during CPB by kallikrein and C5a, but other agonists such as factor XIIa, heparin, leukotriene B_4, IL-1β, IL-8, and TNF also activate neutrophils [267,274,292, 293]. Activated neutrophils release a variety of detrimental substances, including elastase, cathepsin G, lysozyme, myeloperoxidase, defensins, acid hydrolases, bacterial permeability agent, lactoferrin, collagenase, hydrogen peroxide, hydroxyl radicals, hypobromous acid, and hypochlorous acid [294].

Monocytes

Monocytes are activated by monocyte chemotactic protein-1 (MCP-1), C5a, immune complexes, endotoxin, and IL-1 [295, 296]. Activated monocytes express tissue factor, both in the perfusion circuit and in the surgical wound [297]. In addition, these monocytes produce a variety of cytokines (e.g., IL-1, IL-6, and TNF-α) that peak in concentration several hours after CPB [298, 299]. The number of circulating monocytes is not changed during CPB, but this number increases for several hours after CPB [300, 301].

Lymphocytes

The numbers and function of both B and T cells are decreased in the first few days after CPB [302–304].

Consequences of hypothermia

Mild to moderate hypothermia (25–34°C) is used in conjunction with CPB to provide some degree of organ protection from ischemic injury during the operation. This safety margin with respect to organ ischemia is provided by a temperature-related reduction in the organs' oxygen demand and consumption [305]. In neural tissues, there is also a direct beneficial effect of hypothermia in terms of preservation of high-energy stores and a reduction in excitatory neurotransmitter release [306–309]. Because of a reduction in the body's oxygen consumption during hypothermia, CPB can be maintained with lower flow rates. The use of lower flow rates produces several important benefits for the patient and surgeon, including less blood trauma and better visualization in the operative field [310, 311].

Hypothermia produces a variety of effects in the body's organs [312]. In nearly all tissues, hypothermia decreases the organ blood flow, but this effect is pronounced for the skeletal muscle, kidneys, splanchnic bed, heart, and brain. In the *heart*, hypothermia is associated with heart block and both atrial and ventricular arrhythmias. It is important that the patient's temperature not be allowed to fall precipitously during opening and cannulation because any resulting arrhythmias may be difficult to control before the initiation of CPB. In the *lung*, hypothermia leads to decreased ventilation. In the *kidneys*, hypothermia leads to increased renal vascular resistance. There is a decrease in tubular reabsorption, the urine output may increase, and there is often spilling of glucose into the urine. The adjunctive technique of hemodilution during CPB may improve renal blood flow during CPB and limit renal injury. Hypothermia leads to decreased metabolic and excretory function in the *liver*, but clinically significant liver injury during hypothermic CPB is rare.

Hypothermic CPB often leads to hyperglycemia. Gluconeogenesis and glycogenolysis are increased and endogenous insulin production is decreased. Moreover, hypothermia results in a relative insensitivity to exogenous insulin administration. The surgical team should monitor the serum glucose level closely and administer exogenous insulin, as needed. There is ample evidence that avoiding even modest degrees of hyperglycemia may reduce the incidence of postoperative wound infection [313].

Water and electrolyte changes also accompany hypothermia. Hypothermia leads to a decrease in the free water clearance and serum potassium concentration and to increases in serum osmolality.

Hypothermia produces both systemic and pulmonary vasoconstriction at temperatures below 26°C [195]. Arterio–venous shunts may appear at low temperatures and have a deleterious effect on tissue oxygen delivery. There is an increase in blood viscosity and red blood cell aggregation and rouleaux formation may further reduce tissue oxygen delivery. Attention to proper anesthesia, hemodilution, and administration of vasodilators may help to limit these unwanted effects.

Profound hypothermia and circulatory arrest

For certain cardiovascular operations (e.g., aortic surgery), a period of circulatory arrest is helpful or necessary [305]. During periods of circulatory arrest, the use of profound hypothermia (16–20°C) may help to limit ischemic central nervous system (CNS) neurologic injury. Data regarding a "safe" period of circulatory arrest have been conflicting, but periods as long as 30–45 minutes are relatively well tolerated at deep hypothermia. Neurologic injury after profound hypothermia and circulatory arrest may manifest as choreoathetosis, seizures, transient metabolic encephalopathy, stroke, and neurocognitive disorders.

Every effort should be made to make these techniques as safe as possible for the patient. Circulatory arrest should not be initiated until there has been sufficient time for uniform cerebral cooling. Topical cooling of the head (i.e., packed in ice) may be a useful adjunct. The use of barbiturates and corticosteroids are advocated by many authorities as useful adjuncts as well.

Metabolic consequences of CPB

The use of CPB produces a variety of changes in the endocrine, humoral, and metabolic functions of the body.

Pituitary hormones

The serum concentration of vasopressin (antidiuretic hormone [ADH]) is increased significantly with the use of CPB and persists for several hours postoperatively [314–316]. This exaggerated ADH response may be due to a variety of causes, including transient hypotension at the initiation of CPB, a decrease in the circulating blood volume with the initiation of CPB, and a decrease in left atrial pressure with the initiation of CPB. ADH produces an increase in the peripheral vascular resistance, a decrease in cardiac contractility, a decrease in coronary blood flow, an increase in renal vascular resistance, and an increase in the release of von Willebrand factor [317, 318]. The use of pulsatile perfusion or adjunctive regional anesthetic techniques (e.g., thoracic epidural anesthesia) may blunt, but not eliminate the exaggerated ADH response during CPB [316, 319–321].

Adrenal hormones

During hypothermic CPB, the plasma epinephrine concentration is typically increased tenfold and the plasma norepinephrine level is typically increased fourfold [322, 323]. The increased concentrations of these catecholamines leads to increased peripheral vasoconstriction and changes in intraorgan blood flow [323–327]. The use of deeper anesthesia, regardless of the type of anesthesia, may reduce the catecholamine response to CPB [328–331]. The effect of pulsatile perfusion on the catecholamine response is not clear [323, 332].

Cortisol is released in response to the stress of any major operation, usually with a quick rise in concentration and then a slow fall to baseline within 24

hours [333]. With CPB, cortisol rises to a high concentration during CPB and remains markedly elevated for more than 48 hours postoperatively [334–336]. Some studies have shown a blunted cortisol response with greater degrees of hypothermia [337] and with the adjunctive use of thoracic epidural anesthesia [330, 331]. There is also an increase in adrenocorticotropic hormone (ACTH) in response to CPB [338].

Atrial natriuretic factor

Although there is some conflicting evidence, most studies have shown reduced levels of atrial natriuretic factor during CPB, especially in those patients with high preoperative levels (e.g., those with valvular heart disease) [339–341]. For most patients, there is a relative increase in atrial natriuretic factor that starts during rewarming and persists for up to several days after CPB [339, 341–343]. Outside the setting of CPB, atrial natriuretic factor is released in response to atrial distention and acts to increase glomerular filtration, inhibit renin release, reduce the serum aldosterone concentration, and reduce the arterial blood pressure. In patients undergoing CPB, the normal regulatory mechanisms are lost during CPB and are diminished for the first 24 hours postoperatively [344, 345].

Renin–angiotensin–aldosterone axis

The role of the renin–angiotensin–aldosterone axis during CPB is unclear [346]. For patients undergoing nonpulsatile hypothermic CPB, renin, angiotensin II, and aldosterone concentrations are elevated during and shortly after CPB [347–349]. Angiotensin-converting enzyme concentrations, corrected for the degree of hemodilution, are probably not affected by CPB but are typically lower than normal during rewarming and for some period postoperatively [325, 350]. Most evidence suggests that postoperative hypertension is not related to abnormal concentrations of renin, angiotensin II, or aldosterone [351, 352].

Thyroid hormones

Several studies have documented the presence of *sick euthyroid syndrome* in patients during and after CPB [353]. This syndrome is characterized by decreased T_3 concentrations, normal or reduced T_4 concentrations, decreased free thyroxine, and normal thyrotropin concentrations. Administration of heparin before CPB causes a slight increase in the free serum T_3 and T_4 concentrations because heparin displaces these hormones from various binding proteins [354, 355]. Adjusted for the level of hemodilution, however, T_3 concentrations are not altered by CPB [325]. During normothermic CPB, thyrotropin concentrations are normal, but during hypothermic CPB, thyrotropin levels fall with the initiation of CPB and then rise steadily during the period of CPB [354, 356].

Based on the fact that T_3 regulates the heart rate, contractility, and oxygen consumption, some authorities have advocated the administration of T_3

perioperatively to improve cardiac function. In experimental models, T_3 administration has been shown to improve myocardial contractility after CPB [357, 358]. In human studies, however, the evidence has been conflicting [359, 360].

Other serum changes

With the initiation of CPB, there is a fall in the serum total and ionized *calcium* levels [361–365]. With crystalloid priming solutions, the fall in the calcium concentration is due to hemodilution. Historically, many surgeons and anesthesiologists have favored the administration of calcium empirically at the conclusion of CPB to help with weaning from CPB. The effectiveness of this approach is not certain, however. Excessive calcium administration (i.e., without a decrease in the ionized calcium concentration) may contribute to perioperative pancreatitis and reduce the effectiveness of β-adrenergic receptor agonists [365, 366].

Similar to calcium, the serum concentrations of total and ultrafiltratable *magnesium* also fall with the initiation of CPB [365, 367]. After CPB, serum magnesium levels return to normal only very slowly [364]. In the postoperative period, hypomagnesemia may predispose the patient to the development of both atrial and ventricular arrhythmias, so many authorities recommend empiric replacement or supplementation with magnesium during and early after CPB [367–369].

The serum potassium level can vary considerably during CPB. In the absence of cardioplegia, the serum potassium concentration typically falls during hypothermic CPB. In most patients, however, the use of hyperkalemic cardioplegia solutions will promote a tendency for a rise in the serum potassium concentration during CPB [370]. The serum potassium concentration should be monitored closely during CPB, but a normal concentration is not needed until after CPB and a normal electrical rhythm is needed [371]. After the termination of CPB, there is typically an exaggerated loss of potassium in the urine and the clinician should be alert to this possibility [372].

Effects of CPB on the lung

The lungs are affected by CPB in several ways [373–378]. First, collapse of the lungs during CPB produces atelectasis that may persist postoperatively. Second, the lung is a target organ for the systemic inflammatory response to CPB. And lastly, pulmonary metabolic activity is affected by CPB.

Atelectasis

Atelectasis is the most common pulmonary complication after cardiac surgery [374]. Many patient undergoing cardiac surgical procedures will be predisposed to the development of atelectasis on the basis of a smoking history, chronic bronchitis, obesity, or the presence of pulmonary edema. Even before the initiation of CPB, passive ventilation with a paralyzed diaphragm and a

monotonous ventilatory pattern will predispose the patient to the development of atelectasis.

During a typical cardiac surgical procedure, many technical aspects of the operation itself may contribute to atelectasis. If the left internal mammary artery is used for revascularization, the left pleural space is typically entered. Once the left pleural cavity is exposed, blood and irrigation fluid may collect in the pleural space and cause compression of the lung. Because of this problem, some surgeons advocate an extrapleural dissection of the IMA. Once CPB is initiated, the heart rests on the left lower lobe and this may be one explanation for the high frequency of left lower lobe atelectasis after CPB. Endotracheal suctioning during the procedure may produce mucosal injury and lead to atelectasis. Surfactant may be inhibited during CPB and this, combined with increased lung water due to complement activation, may also predispose the patient to atelectasis.

The degree of atelectasis will vary from patient to patient, but the functional residual capacity (FRC) will decrease by approximately 20% [375]. Because of atelectasis, the arterial–alveolar (A–a) oxygen gradient is elevated after CPB and remains elevated for at least 7 days postoperatively. Intrapulmonary shunting is also increased during CPB. Other mechanical changes that have been observed during or after CPB include a decrease in lung compliance and an increase in airway resistance, but it is difficult to determine the relative contribution of CPB (rather than other aspects of the operation) to these changes. Nonetheless, these changes lead to a situation in which there is increased work of breathing postoperatively.

Efforts to prevent atelectasis during CPB have produced only mixed results. There is some evidence to suggest that avoiding entry into the pleural space(s) may lead to better lung compliance postoperatively. A variety of ventilator management strategies during CPB, including intermittent or low-pressure static inflation of the lungs, have produced conflicting results with regard to postoperative lung function [376]. At the conclusion of CPB, it may be helpful to administer a series of sighs, with airway pressures of $\sim$30 cm H_2O to help reverse any atelectasis that has developed during CPB. After operation, the most effective treatment for atelectasis is positive-pressure ventilation that is provided for most patients as routine care. The clinician should be aware that levels of positive end-expiratory pressure (PEEP) greater than 6 cm H_2O may impair the cardiac output. As an alternative, relatively large tidal volumes (i.e., 12–15 mL/kg) may be helpful. A high A–a gradient postoperatively may also be due to underlying chronic lung disease or due to the presence of pulmonary edema.

Acute lung injury

Soon after the introduction of CPB in the 1950s, a syndrome of acute respiratory failure termed "pump lung" was noted to carry a high mortality rate. This acute lung injury was originally thought to be due to microemboli, but the use of appropriate filters in the perfusion circuit did not eliminate this

complication. Today, most acute lung injury is thought to be mediated by complement activation [377].

There is a significant relationship between the duration of CPB, the degree of elevation of the circulating levels of C3a, and the degree of lung dysfunction after CPB. In animal studies, complement produces pulmonary leukocyte sequestration and intrapulmonary release of thromboxane A_2 that produces pulmonary vasoconstriction and hypertension. There is also an accompanying increase in pulmonary vascular permeability that leads to an increase in lung water.

The incorporation of filters in the perfusion circuit is used to limit microembolization and its contribution to acute lung injury. Leukocyte filters have been used for leukocyte depletion during CPB, with varying effectiveness in preventing postoperative lung dysfunction [378]. Leukocyte depletion of the residual volume of blood in the pump at the conclusion of CPB can also be used to help improve postoperative lung function. Hemodilution and avoidance of pulmonary vascular distention (i.e., with appropriate left heart venting) may also help to improve postoperative lung function.

Renal effects of CPB

Several factors associated with cardiac surgery, including not only CPB but also hypothermia and hemodilution, may produce an adverse effect on renal function postoperatively. The relative contributions of each of these factors remain uncertain. Although the frequency of postoperative renal failure has decreased in recent years, this complication still carries a poor prognosis [379–382]. Not only is there a high associated short- (approximately 50%) and long-term mortality rate, but also this complication typically is associated with other early postoperative complications, prolongs the hospital stay, and is associated with a substantial increase in the cost of medical care [383].

The incidence of postoperative renal failure after cardiac surgery that necessitates dialysis is approximately 1% [380, 384]. Postoperative renal failure has been associated with a variety of preoperative patient-related factors, including impaired renal function, impaired preoperative cardiac function, diabetes, peripheral vascular disease, history of acute rheumatic fever, older patient age, more complex operations (i.e., valvular surgery rather than first time CABG), previous myocardial infarction, and the presence of congestive heart failure [381, 383, 385–389].

The contribution of CPB *per se* to postoperative renal dysfunction is not entirely clear. Hemodilution is thought to increase tissue microcirculatory blood flow and oxygen delivery because of a reduction in the blood viscosity, but this effect has not been demonstrated in the human kidney [390]. Most studies that have examined the effect of varying levels of hypothermia on postoperative renal function have failed to show a relationship [391]. Both animal and clinical studies of pulsatile versus nonpulsatile perfusion have failed to show a relationship between perfusion technique and postoperative renal function [392–396]. With the use of membrane oxygenators and arterial line

filters, there is a reduction in embolism during CPB and this, theoretically, should help to prevent embolic damage to the kidneys during CPB. The most important perioperative factors related to postoperative renal dysfunction are thought to be renal hypoperfusion due to either low perfusion pressures during CPB or to the use of vasoconstrictor agents.

Dopamine administered intravenously at low dose (1–3 μg/kg/min) has been shown to increase renal blood flow. Although the practice of administering dopamine at low dose in the perioperative period is common, there is no conclusive evidence that dopamine can ameliorate postoperative renal dysfunction, whether the agent is administered *before* or *after* the renal dysfunction becomes apparent [397, 398]. Recent studies of the selective dopamine-2 receptor agonist, *fenoldopam*, have shown that this agent, when administered prophylactically to patients undergoing intravenous dye tests, confers a degree of protection from postprocedure renal dysfunction [399, 403]. This benefit has not yet been confirmed in cardiac surgical patients, however. Other agents such as *clonidine* [400], *calcium channel blockers* [401, 402], and *atrial natriuretic peptide analogues* [401, 404] have not shown a convincing benefit in preventing or treating postoperative renal failure.

Neurologic effects of CPB

Neurologic complications after cardiac surgery can be categorized into three general types: encephalopathy, stroke, and neurocognitive disorders [405–408]. The incidence of major neurologic complications after cardiac surgery is reported to be approximately 1–6%, but this figure does not include those with neurocognitive disorders [409–412]. In an alternative, and increasingly popular, classification, these complications have been categorized as type I (cerebral death, nonfatal stroke, new transient ischemic attack [TIA]) or type II (new intellectual deterioration or new seizures) [409]. The development of a major neurologic complication is associated with a substantial higher perioperative mortality rate, a prolonged hospital stay, and markedly increased in- and out-of-hospital medical costs [409, 410, 413].

Identified risk factors for the development of a type I neurologic complication include proximal aortic atherosclerosis, a history of previous neurologic event (e.g., TIA, stroke), use of an intra-aortic balloon pump (IABP) during the surgical procedure, diabetes mellitus, hypertension, pulmonary disease, unstable angina, increasing patient age, perioperative hypotension, and the use of LV venting during the operation [409]. Increasing patient age may be the most important risk factor, with an approximately 2% risk of a type I neurologic complication at age 40–49 but an approximately 8% risk at age 70–79 [409]. Although there is some overlap, the risk factors for the development of a type II neurologic complication are somewhat different: increasing patient age, pulmonary disease, hypertension, history of excessive alcohol consumption, history of previous CABG, arrhythmias, history of PVD, and CHF on the day of operation.

In recent years, it has become apparent that neurocognitive (type II) complications are probably much more common than type I complications. At the time of discharge from the hospital, the prevalence of neurocognitive decline may be as high as 60%, depending on the testing methods used to document this complication [414–416]. In the early postoperative period, the results of testing may be influenced by poor patient cooperation due to pain, sleep deprivation, and the effects of medications. Deficits have been documented in psychomotor speed, attention and concentration, new learning ability, and short-term memory. These neurocognitive changes may persist for months after operation and have an immeasurable effect on the individual patient's quality of life.

Considerable efforts have been made to understand the relative contributions of many perioperative factors on the development of neurologic complications after CPB. Nonetheless, it has been difficult to dissect out the individual contributions of potentially detrimental factors such as embolization, hypoperfusion, hypoxia, hypotension, arrhythmias, disorders in coagulation, dehydration, and inflammation. All patients undergoing CPB probably experience some degree of embolization, despite the presence of filters in the perfusion circuit [413, 417–419]. Transcranial Doppler has been used to document the significant relationship between the rate of cerebral embolization during CPB and the risk of a subsequent neurologic complication [417]. There is no convincing evidence that the mean perfusion pressure during CPB is related to the risk of neurologic complications [420, 421], but there can be no doubt that hypoperfusion regionally or in the microvasculature can contribute to neurologic injury. Recently, there has been increased attention to the systemic inflammatory response and its effect on the brain [422]. Several potential neuroprotective agents, including thiopental, propofol, and nimodipine, have been suggested, but there is little evidence for their effectiveness [422]. It may be the case that inflammatory mechanisms may be as important as embolism in the etiology of neurologic complications after CPB.

Several aspects of the conduct of CPB have a bearing on neurologic function and the development of neurologic complications after CPB. In the non-CPB setting, the brain is able to autoregulate cerebral blood flow with a mean arterial pressure of as low as 50–55 mm Hg. Given the lack of reliable evidence linking *mean perfusion pressure* and neurologic outcomes, it is prudent to target the arterial perfusion pressure to be at least in this autoregulatory range. It is probably prudent to maintain the mean perfusion pressure higher for patients at increased risk of cerebral hypoperfusion (e.g., known cerebral vascular disease, previous stroke). Although there has been some conflicting data, most reports suggest that the *systemic temperature* during CPB probably has little independent effect on the frequency of postoperative neurologic complications, at least for degrees of moderate hypothermia (28°C) through normothermia (37°C) [416, 423–425]. Systemic rewarming at the end of CPB should be conducted to avoid even small degrees (i.e., 39°C) of systemic hyperthermia. Although higher *glucose concentrations* in experimental models have been

associated with worse neurologic outcome, studies have failed to document this association in the clinical setting of CPB [416, 426, 427]. It is prudent to maintain the glucose concentration in the physiologic range of 150–250 mg/dL. There are conflicting reports on the effect of *pH management* during CPB in adult patients and the risk of neurologic complications [428, 430, 431]. For adult patients at high risk for embolic events undergoing CPB at moderate hypothermia, alpha-stat pH management may be beneficial in reducing the embolic risk [429].

Despite the considerable morbidity that accompanies neurologic injuries after CPB, it is not a common practice to monitor for the development of these complications *during* CPB. Although the technical details are beyond the scope of this chapter, the methods that are available for this purpose include measurement of jugular bulb oxyhemoglobin saturation [432]; near-infrared spectroscopy (NIRS) [433]; transcranial Doppler [434]; and electrophysiologic monitors such as EEG and evoked potentials [435].

Complications of cardioplegia

Pathophysiologic aspects of myocardial ischemic injury

In the beating heart, the myocardial oxygen consumption (M_{vO2}) is a function of the heart rate, the stroke work, and the inotropic state [436, 437]. During a typical cardiac surgical procedure, the M_{vO2} varies significantly. The M_{vO2} is lowest when the heart is arrested and is greatest just after release of the aortic cross-clamp, when an oxygen debt must be repaid. The M_{vO2} is also influenced by temperature, with markedly decreased M_{vO2} at lower temperatures. Myocardial ischemia occurs when there is an imbalance between myocardial oxygen delivery and myocardial oxygen consumption. Anaerobic metabolism results in acidosis, mitochondrial dysfunction, and, eventually, myocardial necrosis. ATP stores are reduced almost immediately, there is impaired contractility after a few minutes, and there is irreversible myocardial injury after 30–40 minutes of warm (37°C) ischemia. In its severe forms, this myocardial injury can be apparent visually in the operating room, with discoloration of an affected region of the heart. TEE may document regional wall motion abnormalities that are due to regional myocardial ischemia. Postoperatively, this injury can be documented by a rise in the serum creatine kinase (CPK), its myocardial (MB) isoform, lactate dehydrogenase (LDH), and troponin [438]. The peak of the CPK curve is usually at 24 hours after injury, but the LDH peak may occur 4–5 days after injury. The incidence of perioperative myocardial infarction, documented by elevation of the cardiac enzymes, is approximately 1–2%.

There is a spectrum of myocardial dysfunction after cardiac surgery and some myocardial injury may be reversible. Myocardial "stunning" refers to the situation in which initially dysfunctional ischemic myocardium regains normal function after some period of time. For some patients, this situation may be a manifestation of poor myocardial protection during the operation.

For patients with substantial amounts of stunned myocardium, it may take hours or days for this recovery to occur. This condition can be manifested by a low cardiac output syndrome that may require inotropic or IABP support until the myocardium has recovered.

Myocardial protection

The earliest cardiac operations were performed on the beating heart. It was the introduction of CPB and controlled arrest of the heart that enabled complex coronary and intracardiac operations to be performed routinely. The use of a hyperkalemic "cardioplegia" solution was first described in 1955. At that time, very high concentrations of potassium resulted in severe cardiac injury and these solutions were abandoned [3]. For operations that required a "still" heart, fibrillatory arrest induced by hypothermia was widely used. It was not until the 1970s that cardioplegia solutions with lower potassium concentration were shown to avoid direct cardiac injury during use [439, 440]. These solutions have enjoyed widespread use because asystolic arrest significantly reduces the myocardial oxygen consumption. Despite years of study, there are still clinical challenges in the area of myocardial protection [441]. In most applications, intermittent doses of cardioplegia are delivered to satisfy the low-level oxygen and substrate demands of the myocardium during cardioplegic arrest.

Historically, hyperkalemic crystalloid solutions were used to achieve and maintain cardioplegic arrest of the heart. More recently, blood cardioplegic solutions in which oxygenated blood is mixed (1:1 to 8:1) with a hyperkalemic crystalloid solution have become the standard. In animal studies, blood cardioplegia has been shown to reduce irreversible myocardial injury, reduce anaerobic metabolism, preserve high-energy phosphate stores, and result in better postischemic ventricular function compared to crystalloid cardioplegia solutions [442, 443]. Moreover, clinical studies of blood versus crystalloid cardioplegia have shown better outcomes (e.g., reduced perioperative MI, less postoperative low cardiac output syndrome, and improved operative mortality rates) for blood cardioplegia [444].

Historically, cold cardioplegia solutions were used most commonly because of the added benefit of reduced oxygen consumption in the colder myocardium. Often, cardioplegia solutions were supplemented with topical cold saline or slush to help ensure cooling of the myocardium. If cold saline or slush is used, however, the surgeon must be aware of the small risk of phrenic nerve injury due to cold injury [445–447]. If phrenic nerve paralysis occurs, the patient may require prolonged mechanical ventilation and other respiratory complications are more likely. More recently, it has been recognized that lowering the temperature of the myocardium provides only a small additive benefit in terms of oxygen consumption on top of cardioplegic arrest at normothermia [448]. This feature, combined with the finding that myocardial cooling results in slower recovery of postischemic ventricular function, has

prompted many surgeons to move toward the use of normothermic (37°C) or tepid (~34°C) cardioplegia solutions.

Antegrade cardioplegia

Antegrade cardioplegia is administered directly into the aortic root. A purse-string suture is typically placed in the ascending aorta and a cardioplegia cannula or needle is introduced to deliver the cardioplegia. Cardioplegia is typically administered in an initial dose (to cause arrest of the heart) followed by maintenance doses every 15–30 minutes afterward. In practice, the maintenance doses are usually given between anastomoses for CABG operations and at convenient points during valve or other procedures. The perfusion pressure is monitored by the perfusionist and should be maintained at approximately 70 mm Hg. An inability to maintain an adequate perfusion pressure during administration of the cardioplegia solution during the initial dose may indicate aortic insufficiency. The perfusionist should be alert to this possibility, and the surgeon should be vigilant for dilatation of the left ventricle that results from aortic valve insufficiency. If this occurs, intermittent dosing (with interspersed periods of aortic root venting), manual closure of the aortic valve (by pinching the base of the heart), or the use of retrograde cardioplegia may be necessary. Before each maintenance dose of antegrade cardioplegia, the aortic root should be de-aired to prevent air entry into the coronary arteries.

Cardioplegia achieves its desirable effects (e.g., cardiac arrest, cardiac cooling) by distribution throughout the myocardium. The distribution of the cardioplegia solution in the myocardium will be most complete in territories of unobstructed coronary arteries. To help ensure better distribution of the cardioplegia solution, the use of retrograde cardioplegia should be considered in patients with high-grade coronary stenoses or occluded coronary arteries.

Complications related to aortic root delivery of antegrade cardioplegia are relatively uncommon, but include tearing of the aorta, local hematoma formation, dissection of the aorta, and dislodgment of intraluminal plaque with subsequent embolization. During cannulation, a site free of atherosclerotic disease should be selected; manual palpation, TEE, or epiaortic ultrasound should be used to help guide the surgeon. At the conclusion of the procedure, the cardioplegia cannula should be removed and the site should be secured with a suture. Late aortic dissection or pseudoaneurysm formation at this site is possible.

For most CABG operations performed with the use of CPB, administration of continuous antegrade cardioplegia is not practical. During CABG procedures, continuous antegrade cardioplegia will flow through any unoccluded coronary arteries and will obscure the operative field at the coronary arteriotomy. As with beating heart surgery, a misted blower can be used to "spray away" cardioplegia solution from the operative site if antegrade cardioplegia is administered at a low rate during creation of the anastomoses. During elevation of the heart for construction of bypass anastomoses on the lateral wall

of the heart, kinking of the proximal coronary arteries may limit the ability to administer antegrade cardioplegia.

During operations for aortic valve replacement (AVR), an initial dose of cardioplegia can be administered by cannula in the aortic root as described above. Once the aorta is opened to expose the aortic valve, however, another cardioplegic technique must be selected for subsequent administrations of the cardioplegia solution. Retrograde cardioplegia is used commonly in this situation [449], but ostial perfusion cannulas can be inserted into the coronary ostia to deliver antegrade cardioplegia either continuously or intermittently. If continuous cardioplegia delivery is desired, small, flexible, soft-tipped cannulas can be placed in each of the coronary ostia and sutured in place with fine silk or Prolene suture. These cannulas can be held out of the way with additional sutures. If intermittent cardioplegia delivery is satisfactory, the left and right coronary ostia can be cannulated successively with handheld ostial perfusion cannulas. Whenever ostial perfusion cannulas are used, the perfusionist must be vigilant to the pressure of delivery and the surgeon must be vigilant for dislodgment of the cannulas. With either continuous or intermittent delivery, direct injury to the coronary ostia may occur and lead to early or late coronary occlusion.

During operations for mitral valve repair (MVR) or replacement, either handheld or self-retaining retractors used for left atrial exposure have the additional effect of rendering the aortic valve incompetent. As a result, maintenance doses of antegrade cardioplegia can be administered only if the retraction is released and the aortic root is vented of any air. This obviously disrupts the flow of the operative procedure. Most surgeons choose to use retrograde cardioplegia in this situation.

Retrograde cardioplegia

The use of retrograde cardioplegia has come into widespread use, largely because of the problems with distribution of antegrade cardioplegia in situations with occlusion or high-grade stenoses of the coronary arteries [450, 451]. Typically, the retrograde cardioplegia cannula is inserted through a purse-string suture in the right atrium and correct placement of the cannula in the coronary sinus is confirmed by palpation and/or TEE. If a balloon-tipped cannula and pressure monitoring line are used, inflation of the balloon should result in "ventricularization" of the pressure waveform. The cannula should be placed in the most proximal position in the coronary sinus that allows proper fixation. Unlike antegrade cardioplegia, one particular advantage of retrograde cardioplegia is that repeated de-airing of the aortic root is not necessary.

Because of the position of the posterior interventricular vein in the proximal portion of the coronary sinus, this vein will not receive cardioplegia solution if the tip (and balloon) of the retrograde cardioplegia cannula is passed beyond this vein. This may be the most important drawback of retrograde cardioplegia. If the cannula is advanced too far into the coronary sinus, the right side

of the heart will not be perfused adequately [452–455]. Some authorities have suggested carefully "backing out" the retrograde cardioplegia cannula while cardioplegia solution is administered at a low rate until the posterior interventricular vein is seen to fill. Alternatively, a suture snare can be placed around the coronary sinus, just proximal to the posterior interventricular vein, to prevent migration of the cannula into the right atrium.

During administration of retrograde cardioplegia, the pressure in the coronary sinus should be measured continuously. Effective distribution of the cardioplegia solution requires coronary sinus pressures in the 25–40 mm Hg range. Excessive pressure in the coronary sinus may cause localized disruption of this vessel and lead to hemorrhage [456]. When elevating or retracting the heart with a retrograde cardioplegia cannula in place, care should be taken to avoid direct injury of the coronary sinus with the cannula tip. Visible injuries to the coronary sinus should be repaired with fine suture. Occasionally, coronary sinus injuries remain occult until excessive blood is noticed in the pericardial sac at the conclusion of the operative procedure. Another unusual complication of retrograde cardioplegia that has been reported is inadvertent puncture of the inner wall of the right atrium [457].

Neurologic protection

Profound hypothermia and circulatory arrest are helpful for a variety of cardiovascular operations. A variety of adjuncts are available to help prevent neurologic injury during these operations and are discussed elsewhere. Two adjuncts that relate to CPB are profound hypothermia and the use of retrograde cerebral perfusion.

Profound hypothermia

During many routine cardiac surgical procedures (e.g., CABG, valve replacement/repair), the systemic temperature can be maintained at normothermia (37°C) or at mild hypothermia (32–36°C) to avoid the unwanted effects of systemic hypothermia. For operations on the aortic arch or thoracoabdominal aorta, however, an "open" approach is often necessary and profound degrees of hypothermia (16–20°C) with circulatory arrest can be used to reduce the cerebral or spinal cord oxygen requirements and help to limit neurologic injury during the operation. The "safe" period of circulatory arrest at profound degrees of hypothermia is probably 30–45 minutes [458–461]. Longer periods of circulatory arrest have been associated with increased risk of neurologic injury.

Some operations are only possible with the use of profound hypothermia and circulatory arrest. Nonetheless, profound hypothermia has a detrimental effect on platelet function and myocardial recovery postoperatively.

Retrograde cerebral perfusion

Another adjunct that may be useful during periods of profound hypothermia and circulatory arrest is retrograde cerebral perfusion [462–468]. There is

considerable debate about the practical details, however. In its typical application, a venous cannula or a cardioplegia type cannula is inserted into the superior vena cava. A tape or snare is secured around the cannula and retrograde perfusion can be established. The perfusion should be measured and maintained in the range of 25–30 mm Hg [469].

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CHAPTER 5

Myocardial Protection: Why and How

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Cardiac surgery should be safe, simple, and speedy. Operative techniques are constantly being refined, which simplify and expedite formerly complex procedures. In spite of these advancements, the outcome after a technically perfect operation is ultimately dependent upon avoidance of intraoperative damage that impairs cardiac function. Myocardial protection is of paramount importance in achieving this goal. In this chapter, we shall review current concepts of protection and provide the rationale and strategy of our approach to this issue.

Available techniques for myocardial protection often seem complex, and there are proponents of several apparently contradictory methods, including the use of warm versus cold cardioplegia, substrate enhanced versus nonenhanced cardioplegia, antegrade versus retrograde, and intermittent versus continuous delivery. Each is useful depending on the momentary physiologic needs of the heart during a surgical procedure. The technique that is described below is called the "integrated method" of protection and combines the advantages of these approaches. It allows uninterrupted operating, unimpaired vision, unnecessary ischemia, and discontinuation of bypass shortly after aortic unclamping.

Cardioplegia: the basics

Electromechanical activity must be prevented during cardiac procedures. Cold cardioplegia arrests the heart and reduces oxygen demand. It must be delivered in sufficient quantity to all regions of the heart to match this low demand (Figure 5.1). Hypothermia alone, however, does not avoid injury in chronically energy-depleted ischemic hearts.

Cold blood cardioplegia (10°C) consists of four parts of blood to one part crystalloid solution, thereby limiting hemodilution. It maintains oncotic

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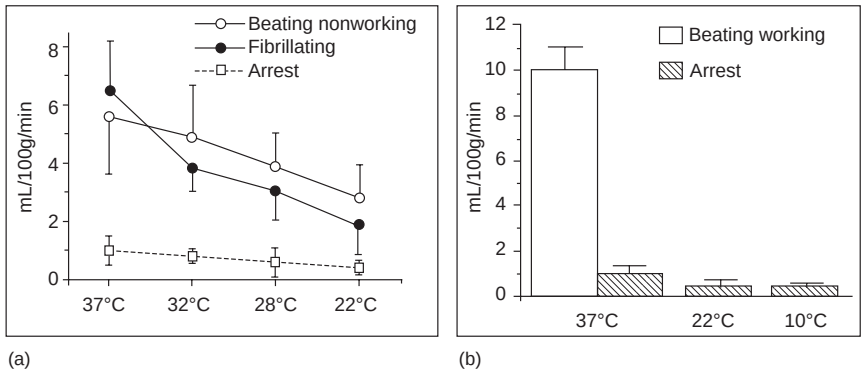

Figure 5.1 Left ventricular oxygen requirements of the beating, empty, fibrillating, arrested heart from 37°C to 22°C. Note the lowest requirements during arrest. Note in (b) the low oxygen demands of arrest and the negligible change between 22°C and 10°C as the heart rewarms from collateral flow. There are higher oxygen demands if electromechanical activity recurs when warm systemic perfusate washes out the cardioplegic solution.

pressure, is a buffering agent, has advantageous rheological properties, and is a free radical scavenger. Blood cardioplegia limits reperfusion injury and reverses ischemia and reperfusion changes in the acutely ischemic myocardium. Hyperosmolarity counteracts edema and may enhance myocardial compliance postoperatively [1]. These beneficial features have not been demonstrated with crystalloid cardioplegia, which shifts the oxyhemoglobin association curve leftward, retarding Na^+/K^+ adenosine triphosphatase, thereby producing edema and activation of platelets, leukocytes, and complement.

Warm blood cardioplegia (37°C) given initially (induction) limits reperfusion damage in ischemic hearts. It enhances metabolic repair by channeling aerobic adenosine triphosphate production to reparative processes. Components are added to the cardioplegia for their protective effects. Citrate phosphate dextrose (CPD) limits calcium influx during ischemia, which can damage sarcolemma membranes. Tromethamine (tris-hydroxymethyl aminomethane or "THAM") is a buffer that prevents acidosis. THAM diffuses into the intravascular space and captures the CO_2 produced by metabolic acidosis and improves myocardial performance. Warm cardioplegic induction and reperfusion solutions are further enhanced with the amino acids glutamate and aspartate, which replenish key Krebs' cycle intermediates depleted by ischemia. These additions augment the reparative processes after a period of myocardial ischemia [2, 3] (Figure 5.2).

Multidose cardioplegia

Cold blood cardioplegia is delivered every 10–20 minutes because warm systemic blood from noncoronary collateral flow can displace the cardioplegia

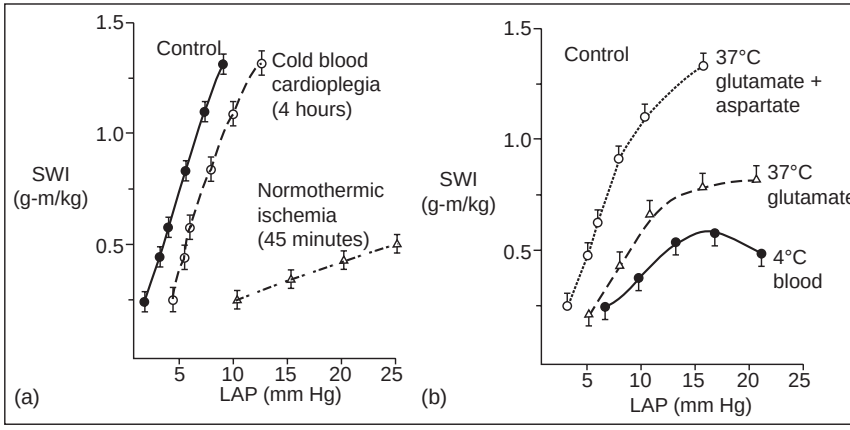

Figure 5.2 (a) Left ventricular function in normal hearts subjected to 4 hours of aortic clamping with cardioplegia utilizing blood every 20 minutes compared with depressed function after 45 minutes of normothermic arrest without cardioplegia. The type of protection is more important than the duration of aortic clamping. (b) Left ventricular function when jeopardized hearts undergoing 45 minutes of normothermic ischemia are subjected to 2 more hours of aortic clamping. Note (i) no further improvement when only cold cardioplegic perfusate is given over the arrest period, (ii) progressively increased recovery when the cardioplegic solution is supplemented with warm glutamate and aspartate during induction of cardioplegia and reperfusion with intermittent cold doses of blood every 20 minutes of supplemental aortic clamping. These data suggest the value of amino acid enrichment in jeopardized hearts. LAP, left atrial pressure; SWI, stroke work index.

solution within the myocardium. Frequent infusions of cardioplegia maintain cardiac arrest and restore substrates that are depleted during ischemia.

Cardioplegia delivery

Cardioplegia is effective only if it is well distributed [4]. Transatrial coronary sinus cannulation allows safe and rapid retrograde cardioplegia delivery and is widely used. Adding retrograde perfusion improves subendocardial perfusion, avoids ostial cannulation during aortic valve procedures, limits removal of retractors during mitral procedures, and permits flushing of coronary air during coronary bypass procedures. Right ventricular nutritive flow is limited by retrograde cardioplegia since the delivery catheter is usually placed distal to the venous tributaries of the right coronary artery. However, the right ventricle is cooled during delivery of retrograde cold cardioplegia by its proximity to the cooled septum in the decompressed vented heart. Clinical studies show that switching from antegrade to retrograde perfusion raises oxygen uptake and lactate washout, indicating that each mode perfuses different areas of the myocardium. Therefore, both antegrade and retrograde perfusion are required [3] (Figure 5.3).

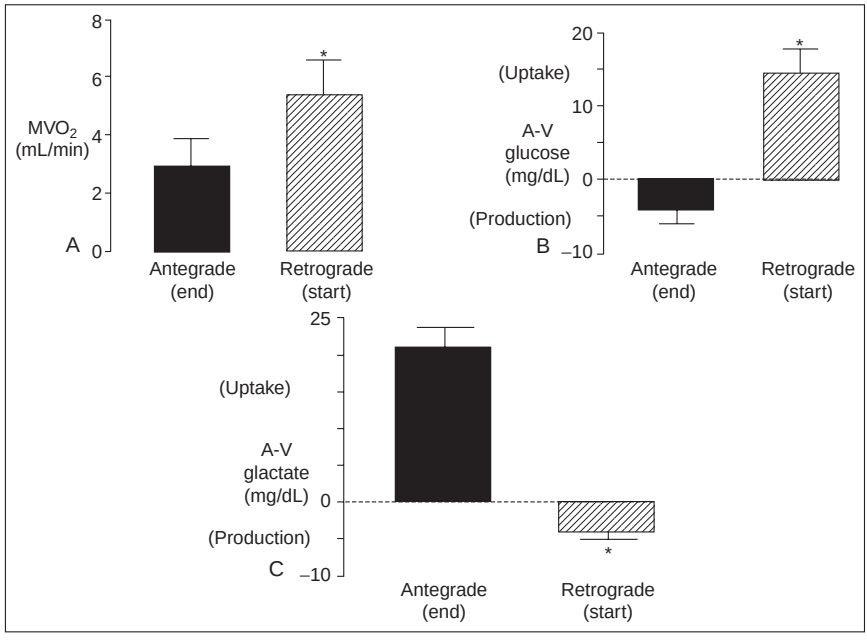

Figure 5.3 Myocardial metabolic changes in coronary bypass patients during delivery of the cardioplegic induction solution antegrade and retrograde. Note the increase in myocardial oxygen uptake (MVO_2), glucose uptake, and lactate production, suggesting different areas of perfusion by the antegrade and retrograde methods of delivery. This implies an advantage to both methods.

Alternating between antegrade and retrograde cardioplegia delivery is an acceptable method. Simultaneous antegrade and retrograde delivery can, however, be especially helpful. For example, following saphenous vein anastomosis to a coronary artery, cardioplegia may be delivered through the vein graft and simultaneously into the coronary sinus. Myocardial venous hypertension is prevented by drainage through the Thebesian veins.

Continuous cardioplegic perfusion has been advocated to avoid ischemia by antegrade or retrograde delivery, but adequate protection may not be achieved at usual flow rates and vision becomes obscured during infusion. A dry operative field requires "intentional" ischemia by intermittently stopping the flow of cardioplegic solution. Intermittent replenishment restores hypothermia, flushes accumulated metabolites, and counteracts acidosis and edema.

The "integrated method" of cardioplegia

The integrated method of cardioplegia combines the advantages of many strategies while addressing the momentary needs of the myocardium during a cardiac operation. This technique is easily applied and hastens the recovery of the myocardium while not interfering with visualization while suturing [5].

Table 5.1 Cardioplegia Solutions (administered as four parts blood to one part cardioplegia solution)

Ingredient	*Cold induction and warm reperfusion "Bag 1"*	*Maintenance "Bag 2"*	*Modified cold blood "Bag 3"*	*Acute MI/Arrest "Bag 4"*
Na/Glutamate/Na Aspartate 0.46 M	188 ml			125 ml
Dextrose 50% Water	30 ml			20 ml
Dextrose 5% Water	184 ml			122.5 ml
Tromethamine 0.3 M Solution	169 ml	200 ml	50 ml	112.5 ml
Citrate Phosphate Dextrose	169 ml	50 ml	50 ml	112.5 ml
Dextrose 5% in $\frac{1}{4}$ Normal Saline		550 ml		
KCl (2 mEq/ml)	66 Meq	30 Meq		15 Meq
Isolyte S			1000 ml	
Mannitol 25%			50 ml	
Magnesium Chloride 20%	4.5 ml	4.5 ml	8 ml	
Diltiazem				300 mcg/kg
Total Volume	778 ml	820 ml	1158 ml	493 ml

Delivery of Cardioplegia

	Antegrade perfusion	*Retrograde perfusion*
Induction		
Cold	300 ml/min x 2 min	200 ml/min x 2 min
Warm	300 ml/min until arrest, then 150 ml/min x 2.5 min	150 ml/min x 2.5 min
Maintenance	200 ml/min x 1 min	200 ml/min x 1 min
Warm Reperfusion	150 ml/min x 2 min	150 ml/min x 2 min
Modified cold blood	200 ml/min	200 ml/min

A typical three-vessel coronary bypass operation is first illustrated. Initially, following aortic clamping on cardiopulmonary bypass, the heart is arrested with "induction" high-dose potassium (20 mEq/L) cold blood cardioplegia (bag 1, Table 5.1) infused antegrade into the aortic root at a flow rate of 300 mL/min for 2 minutes, followed by retrograde coronary sinus infusion at a flow rate of 200 mL/min for 2 minutes. Septal temperature is monitored with a temperature probe and usually falls to below 15°C. Right ventricular topical hypothermia can be supplemented with cold saline or iced saline slush with care taken to protect the phrenic nerves. This is not, however, mandatory. The right coronary is first grafted with saphenous vein. "Maintenance" low-dose cold potassium (8–10 mEq/L) blood cardioplegia (bag 2, Table 5.1) is then infused simultaneously into the vein graft and coronary sinus at a flow rate of 200 mL/min for 1 minute [6]. The vein graft is then sewn onto the aorta while a continuous noncardioplegic solution of cold blood is infused at 200 mL/min. This "modified cold blood solution" (10°C) contains CPD, THAM, magnesium, and mannitol, and has been shown to provide better recover

than cold blood alone [7] (bag 3, Table 5.1). The aorta is vented through the cardioplegia delivery catheter, which is directed toward the posterior aorta, thereby harvesting the blood returning into the aorta. This allows good visualization during proximal grafting of the vein to the aorta. Next, maintenance cardioplegia (bag 2) is infused into the aortic root at a flow of 200 mL/min while the surgeon inspects the heart for the next bypass target. The aorta is vented while the next distal coronary is grafted. The above procedure is repeated until all grafting is complete reserving the last proximal vein graft anastomosis. During mammary grafting to the left anterior descending artery (the last distal anastomosis), rewarming of the body and cardioplegia is begun.

Next, the "hot shot" of warm substrate-enhanced cadioplegia (bag 1, Table 5.1) is delivered first antegrade into the ascending aorta at 150 mL/min for 2 minutes, then retrograde through the coronary sinus and simultaneously through the last unattached saphenous vein graft at 150 mL/min. for 2 minutes. The added amino acids often causetransient mild vasodilatation, which is treated with low-dose infusion of neosynepherine (0.5–1 mcgm/kg/min). The last proximal vein graft is then sewn to the aorta while the cardioplegia is washed out of the myocardium by retrograde infusion of plain warm blood at a flow of 300 mL/min [8].

The heart resumes contractility during warm retrograde blood infusion. After the last saphenous graft is sewn to the aorta, warm blood is then infused directly into the aorta with the aortic clamp still in place at a flow rate of 300 mL/min for about 5 minutes or less until vigorous contractility is observed. Air is purged out of the ascending aorta just before the last proximal suture is tied. Air is also purged from the coronary grafts with a fine needle. The aortic clamp is thenremoved and the patient weaned off bypass, usually within 5 minutes with minimal (dopamine 2.5 mcg/kg/min) or no inotropic support in spite of lengthy aortic clamp times. Defibrillation is very rarely needed.

During valve operations, the same general methods apply. The heart is arrested with cold blood induction cardioplegia, administered antegrade or retrograde (bag 1, Table 5.1). During aortic valve replacement, if aortic regurgitation is present, cardioplegia is delivered retrograde, supplemented by infusion of cardioplegia directly into the coronary ostia with handheld devices. During mitral valve surgery, intermittent doses of antegrade and retrograde maintenance cardioplegia (bag 2, Table 5.1) are given. The integrated method meets the momentary needs of the myocardium while not hampering the course of the operation. For example, while the sutures are placed into the sewing ring of a prosthetic valve, retrograde modified cold blood solution (bag 3, Table 5.1) can be continuously infused. This keeps the heart cold and washes out metabolites. When the valve is lowered into place and sutures are tied, a dry field is needed and so the infusion is stopped. The same general methods are used during replacement of the aorta. At no time is cardioplegia administered while the surgeon is suturing on or in the heart.

Single period of aortic clamping

The integrated method of protection is always done with a single period of aortic clamping as described in the prior section. This has been shown to limit atheroembolic events. While it may seem that the ischemic time is increased by this method, the contrary is true. Morbidity and cost are reduced despite a longer aortic clamp time when using this technique [9]. These findings contradict the notion that there is a constant battle against the clock when the aorta is clamped. The extent of cardiac damage is related to *how* the heart is protected rather than *how long* the aorta is clamped. Blood cardioplegia delivered antegrade and retrograde provides sufficient cardiac nourishment during aortic clamping to limit ischemia and does not slow the operation, since each is applied in a timely manner to assure a dry operative field.

Cannulas and devices for cardioplegia delivery

All operations include the use of a cardioplegic heat exchanger for cold and warm perfusion (Figure 5.4), cannulas for antegrade and retrograde delivery, and a monitoring–infusion system. A typical setup is shown in Figure 5.5. There are three main controls for the surgeon:

1 A stopcock that switches between antegrade and retrograde infusion. Infusion lines are attached to thinner lines for measuring infusion pressures.

2 A flow clamp to activate the aortic vent.

3 A flow clamp on the retrograde infusion line, which controls infusion of cardioplegia through the vein graft or through a handheld catheter placed into the coronary ostia during aortic valve procedures. Additional lines can be attached to either the antegrade or retrograde lines if needed.

Antegrade cannula

An antegrade cannula is placed high in the right ascending aorta and slightly below the anterior surface. This site is not used as a proximal graft site. A 3-0 mattress suture with a tourniquet is used to secure the cannula and tied at the end of the procedure. The cannula contains a pressure line and a vent port to suction air and blood between infusions. During proximal grafting of the saphenous vein to the aorta, continuous retrograde blood is infused into the coronary sinus. Low active suction through a "pop-off" valve (approximately 175 mm Hg) in the vent line keeps the blood level to just below the proximal suture line permitting excellent visualization during proximal grafting of vein to the aorta.

Retrograde cannula

Transatrial cannulation of the coronary sinus obviates the need for right heart isolation and atriotomy. Cannulation is performed after systemic venous

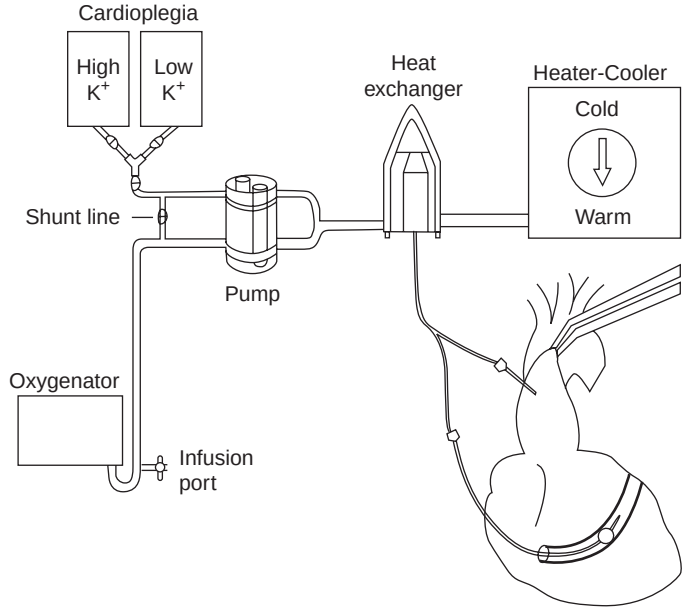

Figure 5.4 Blood cardioplegic delivery system: the cardioplegic solutions are listed in Table 5.1. Cold blood is mixed with cardioplegia solutions as a 4:1 mixture. The shunt line allows delivery of regular blood through the roller head of the pump after the warm reperfusate ("hot shot") is given.

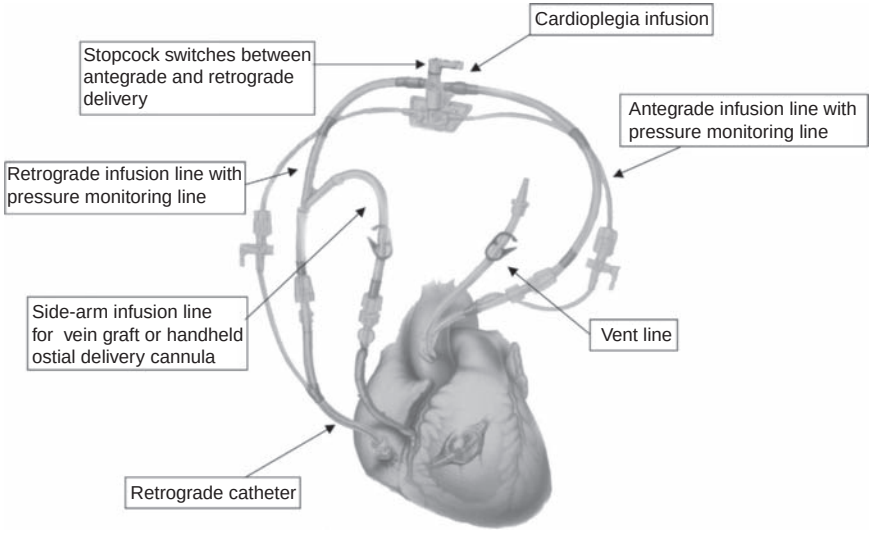

Figure 5.5 Cardioplegia delivery system.

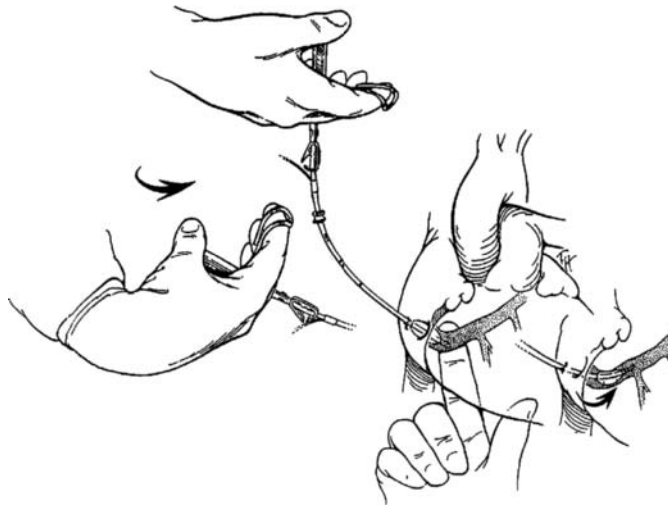

Figure 5.6 Method for introducing the retrograde cannula from the surgeon's side. Note that the cannula is rotated anteriorly and toward the left shoulder to follow the course of the coronary sinus.

cannulation and takes a few seconds. We use a malleable stylet placed through a self-inflating balloon cannula and introduce it anterior to the two-stage venous cannula. A purse-string suture is first placed low in the right atrium and the cannula is inserted into the coronary sinus, usually before commencement of cardiopulmonary bypass. We often retract the atrioventricular groove superiorly and to the left while inserting the cannula. The suture is then tightened through a tourniquet.

The cannula is directed at an angle of 45° toward the left shoulder in the path of the coronary sinus and positioned distally beneath the left atrial appendage. The cannula tip is palpated as it passes by the junction of the inferior vena cava and right atrium into the coronary sinus (Figure 5.6). If the cannula is directed into the posterior descending vein, it should be withdrawn slightly and reinserted. If difficulty is encountered during placement, it is helpful to commence cardiopulmonary bypass and lift the apex of the heart cephalad. The cannula can then be inserted into the coronary sinus by visualization and palpation while keeping the atrium filled. In reoperative surgery, the retrograde cannula can be placed without palpation prior to cardiopulmonary bypass (CPB) if the posterior ventricle has not yet been dissected off of the diaphragm. Alternatively, after CPB is instituted, the heart can be freed and the cannula positioned as in nonreoperative cases.

Failure to intubate the coronary sinus is rare (under 2% of cases) and indicates a fenestrated thebesian valve or a flap over the coronary sinus ostium. When this occurs, bicaval cannulation may be used. The right atrium is opened with a small incision and cannulation performed directly after the flap is retracted or the thebesian valve is opened.

During retrograde infusions, the posterior descending vein fills readily with oxygenated red blood. The cannula is withdrawn slightly if this is not observed, or if the pressure exceeds 40 mm Hg.

Coronary sinus injury

The coronary sinus can be injured due to forceful cannulation or continued infusion of cardioplegia with coronary sinus pressure exceeding 40 mm Hg. The perfusionist first notes high coronary sinus pressure followed by low pressure after the sinus perforates, or the surgeon sees red blood within the pericardial well during infusions. Perforation can be directly repaired with a 5-0 suture or with pericardial pledgets if the tear site is not distinct. If a hematoma is noted, retrograde infusions should be discontinued. No further action is needed because low venous pressure allows self-containment after heparin reversal.

Monitoring antegrade cardioplegia delivery pressure

Delivering cardioplegia under high pressure can be deleterious by causing endothelial damage and myocardial edema. Monitoring infusion pressure is absolutely essential to avoid such damage.

Monitoring pressure in the cardioplegia delivery system on the perfusionist's pump allows detection of inadvertent line occlusion by clamping or kinking. However, using the delivery system line pressure to estimate aortic or coronary sinus pressure is inaccurate. Accurate infusion pressure is obtained through a line directly attached to the infusion port. Such systems are widely commercially available.

Antegrade infusion pressure should be kept between 60 and 80 mm Hg. If there is extensive coronary disease, then the pressure may be high during infusion. The flow rate should be reduced and the duration of infusion extended.

If there is mild aortic insufficiency, antegrade cardioplegia will be infused directly into the left ventricle where it will have no effect on protection. In such cases, placing a sponge-stick on the right ventricle and applying mild pressure will close the left ventricular outflow tract. By observing the aortic root pressure during infusion, the surgeon can confirm that cardioplegia is infused into the coronary arteries. If this maneuver is not effective, then cardioplegia is delivered retrograde.

Myocardial temperature should be measured in all cases during cardioplegia delivery. We usually place the probe in the septum, which is the most vulnerable area of the myocardium. It can, however, be readily moved to other areas of the myocardium to assure adequacy of global cardioplegia delivery. Myocardial temperature should be kept below about 15°C. Inadequate cooling can sometimes be seen if a double-staged venous cannula pushes against the noncoronary cusp resulting in aortic regurgitation during cardioplegia infusion. Simply repositioning the cannula in the field will correct this problem.

During the final warm cardioplegia infusion (hot shot), the aortic root pressure should not exceed 50 mm Hg to avoid endothelial dysfunction.

Monitoring retrograde cardioplegia delivery pressure

Coronary sinus pressure during retrograde cardioplegia delivery should be kept between 20 and 40 mm Hg at an infusion rate of 200–250 mL/min. A coronary sinus pressure more than 40 mm Hg indicates improper catheter position. Withdrawing the catheter slightly usually resolves this problem. Coronary sinus pressure less than 20 mm Hg infers that the balloon is not inflated or not occluding the coronary sinus. The cannula tip and balloon should then be palpated and repositioned. Added maneuvers to improve retroperfusion include finger compression of the junction of the coronary sinus and right atrium or placement of a snared suture around the coronary sinus, thus fixing it in place and preventing regurgitation of cardioplegia into the atrium. A rare cause of low pressure is the presence of a left superior vena cava. This is usually determined before CPB and the vessel occluded with a tourniquet only if an intact innominate vein is present. If the innominate vein is absent, only antegrade cardioplegia is used to avoid myocardial underperfusion.

Cardioplegia delivery system

Commercially available delivery systems allow rapid switching from antegrade to retrograde perfusion with corresponding monitoring of aortic and coronary sinus pressures. Such a system is shown in Figure 5.5. The side arm attached to the retrograde line has many benefits during retroperfusion:

1 Cardioplegia can be simultaneously delivered antegrade (via the distally attached saphenous graft, or via the right coronary ostium in aortic procedures) and retrograde via the coronary sinus.

2 The distal suture line can be tested under pressure for leaks during delivery of cardioplegia through the saphenous graft.

3 The saphenous graft can be deaired as the distal suture line is secured during simultaneous retrograde and graft infusion.

4 Graft twisting can be avoided by observing the filled saphenous vein during infusion of cardioplegia

5 Saphenous graft length can easily be determined during cardioplegia infusion.

Evolving myocardial infarction

The procedure is modified in patients with acute ischemia or evolving myocardial infarction. If a coronary artery is totally occluded, the following method limits reperfusion injury to the myocardium. A substrate-enhanced low-potassium cardioplegia is used during these procedures, which we call "acute MI/arrest" cardioplegia (bag 4, Table 5.1). This is a formulation that

contains potassium to keep the heart arrested together with amino acid substrates with the addition of a calcium channel blocker to prevent calcium influx onto the myocardial organelles. This cardioplegia is infused over a prolonged time (20 minutes) to replenish the energy-depleted myocardium.

The left ventricle is first vented via the right superior pulmonary vein to minimize myocardial oxygen demands. CPB is then instituted with body cooling to the usual 34°C. The aorta is clamped and cardiac arrest induced with warm substrate-enhanced cardioplegia (bag 1, Table 5.1) at a flow of 300 mL/min. This is followed by antegrade and retrograde infusions of the same solution, each for 2 minutes. Cold maintenance blood cardioplegia (bag 2, Table 5.1) is then delivered antegrade at a flow of 300 mL/min for 2 minutes and retrograde at a flow of 200 mL/min for 2 minutes as in the usual noninfarcted cases. Grafts are sewn into place in the standard manner with one exception: the saphenous graft to the infarct-related artery is not sewn to the aorta but reserved for delivery of prolonged recovery cardioplegia. A hot shot of warm reperfusion cardioplegia (bag 1, Table 5.1) is again delivered antegrade then retrograde as in the normal coronary bypass operation. The aortic clamp is removed and warm systemic blood perfuses the aortic root and the coronary arteries. The infarct-related artery is then selectively perfused with the "acute MI/arrest" cardioplegic solution through its vein graft (not yet attached proximally to the aorta) for 20 minutes at a flow of 50 mL/min (pressure <50 mm Hg to prevent endothelial damage). The heart resumes contractility, but the infarcted segment remains asystolic due to the prolonged infusion of the acute MI/arrest cardioplegia.

The left ventricle is vented as the heart resumes contractility to assure low oxygen demand. A side-biting tangential aortic clamp can be placed on the aorta as the last saphenous vein is attached to the aorta. Alternatively, the aorta can be clamped and the last vein graft attached to the aorta during retrograde infusion of warm blood.

The surgeon may choose to place an internal mammary artery to the infarct-related artery. In such cases, a saphenous vein is also grafted to the involved coronary artery and used to deliver the enriched solution described above for the 20-min interval. After cardioplegia is infused into the infarcted segment, it can be ligated. Bypass is continued for 20–30 more minutes to allow recovery of the newly revascularized infarcted myocardium.

We have observed significant return of regional contractility despite more than 6 hours of total artery occlusion [10]. Leukocyte depletion by adding filters to the cardioplegia in cases of acute infarction has also been shown to attenuate reperfusion injury. The details and outcome of this technique have been previously described [11].

Myocardial protection during aortic root replacement

The myocardium must be carefully protected during aortic root replacement for dissection or aneurysm disease. Here, the coronary ostia are often isolated

for reimplantation into a prosthetic graft. Intermittent cardioplegia can be administered directly into these unattached ostia by handheld cannulae or self-inflating balloon catheters, but care must be taken to avoid injury particularly if operation is indicated because of dissection. An approach that we have found useful in cases of aortic dissection is first grafting the right coronary artery with saphenous vein. The proximal right coronary artery is temporarily occluded with a silastic vascular loop or soft jaw clamp. Cardioplegia can then be administered intermittently antegrade via the grafted right coronary artery for right ventricular protection and simultaneously retrograde into the coronary sinus for left ventricular protection. This permits excellent cardioplegia distribution throughout the myocardium and does not interfere with visualization during the operative procedure. The aortic root and ascending aorta can be replaced with ease in a dry field. After the root replacement, the saphenous vein graft is ligated at the anastomosis to the right coronary artery, either with a running suture or with a large hemoclip. The extra 5 minutes to execute this protective method assures global myocardial protection and avoids injury to the friable coronary ostia.

Surgical ventricular restoration

Surgical ventricular restoration (SVR) is an operation to treat congestive heart failure in patients with postinfarct ventricular dilation. The ventricle is reshaped by placement of an intraventricular patch that excludes the noncontracting (usually antero-septal) infarcted segment. About 25% of patients undergoing SVR also require mitral valve repair and about 90% require concomitant coronary bypass grafting. Patients undergoing SVR are high-risk patients due to extensive myocardial damage and severe left ventricular dysfunction.

Based on experimental and clinical findings, we approach this operation somewhat differently. The operative approach for myocardial protection is in two parts. During coronary grafting and mitral valve repair, the integrated method of protection is employed. During the ventricular repair, we prefer the "open-beating" method of protection. A catheter placed through the right superior pulmonary vein across the mitral valve into the left ventricle vents the heart. The apex of ventricle is opened and while the heart is beating, palpation and inspection of the myocardium readily defines the segment to be excluded. Mean systemic arterial pressure is kept above 80 mm Hg. Our preference is to use vasoactive drugs and intra-aortic balloon counterpulsation (IABP) when needed to assure adequate myocardial perfusion. The need for this alternate approach came from animal studies, which showed that the distribution of cardioplegia in the opened incised ventricle was not uniform. Clinical data support improved outcomes in the high-risk SVR population [12, 13].

Determination of preoperative aortic insufficiency by ventriculography or echocardiography is critical during SVR surgery because blood will

regurgitate into the operative field and obscure vision during the ventricular repair. If aortic regurgitation is present, we use the open-beating method with some modifications. The aortic clamp is left in place during ventricular repair. The heart is kept beating by continuous perfusion of warm blood via the saphenous grafts, internal mammary artery, and coronary sinus simultaneously [14].

Septal function

Paradoxical septal motion is commonly seen after cardiac surgery. A recent study of over 3000 cases reported an incidence of approximately 40% [15]. Various theories have been proposed over the years to explain this common finding, including release of the pericardium. Alternatively, septal dysfunction can be viewed as a form of injury, either permanent or transient (stunning). We have carefully reviewed over 100 consecutive cardiac surgical procedures, including coronary bypass grafting and valve procedures with 2D echocardiography. Septal dysfunction, either in the form of dyskinesia or hypokinesia, was seen in none of the patients in whom integrated protection was employed and this confirms our hypothesis that septal dysfunction is usually the result of inadequate myocardial protection.

Conclusion

"Integrated myocardial management" is effective in all adult cardiac procedures by expediting the operation and meeting the physiological momentary needs of the myocardium. The duration of CPB is shortened by this technique by eliminating the need for recovery time following unclamping of the aorta. Excellent clinical outcomes have been reported and this method has been widely employed for several years. Ongoing studies will likely lead to the development of additional cardioprotective strategies. These may include the use of preconditioning agents, white blood cell filters, free radical scavengers and endothelium-enhancing agents.

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CHAPTER 6

Complications after Pulmonary Resection: Lobectomy and Pneumonectomy

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Introduction

Pulmonary resections are performed for both diagnosis and treatment for a variety of inflammatory, physiologic, infectious, and neoplastic conditions. The extent of resection ranges from wedge resections to anatomic resections such as segmentectomy, lobectomy, bilobectomy, and pneumonectomy. Advances in surgical and anesthetic techniques and perioperative care have made anatomic lung resections a common and almost routine procedure, with consistent improvements in operative mortality. Despite the observed improvement in mortality, the morbidity rates associated with pulmonary resections have not changed significantly over time. This may actually be an indirect result of improvements in perioperative management, which have allowed lung resections to occur in higher risk patients, such as older patients, patients who received preoperative chemotherapy or radiation, patients with significant comorbidities, and patients with reduced pulmonary reserve.

Most complications are not life-threatening but are associated with prolonged hospitalization and patient discomfort. Attention to detail is required from the initial evaluation throughout the postoperative period to minimize both the occurrence and the morbidity associated with complications, particularly in patients who are marginal resection candidates.

Mortality

The major causes of postoperative mortality following lung resection are cardiovascular and pulmonary complications [1–4]. The operative mortality for anatomic lung resections has steadily decreased over time, likely reflecting improvements in preoperative patient selection, intraoperative techniques, and postoperative care (Table 6.1). In one multi-institution series of patients

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Table 6.1 Perioperative mortality for lobectomy and pneumonectomy.

			Lobectomy		*Pneumonectomy*	
Author [reference]	*Time period*	*Number of institutions*	*Number of patients*	*Mortality (%)*	*Number of patients*	*Mortality (%)*
Weiss [5]	1961–1965	Multicenter	149	10.1	212	17
Nagasaki [6]	1973–1980	Single center	570	2	72	6
Ginsberg [1]	1979–1981	Multicenter	1058	2.9	569	6.2
Deneffe [7]	1970–1985	Single center	352	2.9	287	6.9
Romano [8]	1983–1986	Multicenter	6569	4.2	1529	11.6
Kadri [9]	1980–1987	Single center	280	3.9	191	6.8
Duque [10]	1993–1994	Multicenter	294	4.4	172	13.4
Wada [3]	1994	Multicenter	5609	1.2	586	3.2
Harpole [11]	1991–1995	Multicenter	2949	4.0	567	11.5
Licker [13]	1990–1997	Multicenter	328	1.2	151	7.9
Siegenthaler [14]	1996–1999	Single center	282	3.9	36	8.3
Myrdal [15]	1987–1999	Single center	334	0.6	157	5.7
Perrot [16]	1993–2002	Single center	45	0	55	1.8
Rostad [4]	1993–2002	Multicenter	2372	3.5	852	9.2
Allen [12]	1999–2004	Multicenter	766	1.0	42	0

who had surgery prior to 1974, the operative mortality was 17% for pneumonectomy and 10% for lobectomy [5]. Both single center and multicenter series in the 1970s and 1980s reported lower mortality rates, ranging from 6% to 11.6% for pneumonectomy and 2–4.2% for lobectomy [1, 6–9]. Several more recent series have similar mortality, though mortality rates in other more recent single center and multicenter series are as low as 0–3.2% for pneumonectomy and 0–1.2% for lobectomy [3, 4, 10–16]. The operative mortality in one recent large, multi-institutional study of early stage lung cancer was 0% for pneumonectomy and 1.3% for lobectomy [12]. Table 6.2 lists patient variables that are predictors of mortality after lung resection

Table 6.2 Risk factors for mortality after lobectomy and pneumonectomy.

Age
Male gender
Malnutrition
Diabetes
Chronic lung disease
Coronary artery or other chronic heart disease
Disseminated cancer
Neurologic disorder
Peripheral vascular disease
Intraoperative blood loss
Transfusion greater than 4 units
Excessive perioperative administration of crystalloid fluids

[4, 8, 10, 11, 13, 17–19]. Knowledge regarding the prognostic variables may improve patient selection and avoidance of complications.

Many studies have found patient age to be a risk factor for 30-day mortality after both lobectomy and pneumonectomy, with significant increases in mortality observed both in patients over 60 and over 70 years of age [1, 3, 4, 8, 11, 20–22]. In a report from the Lung Cancer Study Group in 1983, the mortality rate was 1.3% in patients younger than 60 years, 4.1% in patients aged 60–69, and 7.1% in patients older than 70 years [1]. Similar findings were reported in a large, single institution series in 1998, where the mortality by age was 0.4% for patients younger than 60 years, 1.3% for those aged 60–69, 2.0% for those aged 70–79, and 2.2% for those aged 80 or older [3]. However, a more recent large, multi-institutional study did not observe an association between age and mortality [12]. The effect of age in earlier reports could have been due to increased comorbidities in the elderly, and more recent improvements could reflect better patient selection and preparation, as well as improved perioperative techniques that allow older patients to undergo surgery more safely.

Extent of operation is also a mortality risk factor. Pneumonectomy has higher mortality than lobectomy (Table 6.1) [3, 8, 10, 11, 13, 21, 22]. Extrapleural pneumonectomy, with mortality of 3.4–11.2% in recent series from high-volume institutions, also has higher mortality than simple pneumonectomy [23, 24–28]. Completion pneumonectomy, a pneumonectomy preceded by a prior resection from the same lung, also has higher mortality rates of 10–23% [19, 29–34]. The mortality of completion pneumonectomy depends on the indication: completion pneumonectomy has mortality of 10–17.6% for recurrent lung cancer, 23% for chronic mycobacterial disease, and 33.3–37.5% for reoperation for an early complication of another lung resection [31–34]. Right-sided pneumonectomy also has higher mortality compared to left pneumonectomy [6, 19, 28]. The reason for this difference could be that right pneumonectomy has higher rates of major complications, including bronchopleural fistulas, empyema, and postpneumonectomy pulmonary edema [2, 27, 35, 36].

Two other factors associated with patient mortality are the experience of both the surgeon performing the operation and the hospital where surgery is performed. A community-based study found the mortality rate for all patients undergoing pulmonary resection throughout the state of California from 1983 to 1986 to be 4.2% for lobectomy and 11.6% after pneumonectomy [8]. The mortalities from this series, which included all patients regardless of surgeon experience, are higher than series from dedicated thoracic surgery services from the same time frame, suggesting that better results are obtained by dedicated thoracic surgeons [1, 7, 9]. In another study, mortality was significantly higher in patients who underwent lobectomy by general surgeons versus specialty trained thoracic surgeons (5.3% vs. 3.0%) [20]. In addition, high-volume hospitals have better mortality rates than low-volume hospitals [8, 37].

Morbidity

The improvement in mortality since 1970 has not been observed for overall morbidity after lobectomy and pneumonectomy (Table 6.3). Prospective studies have found complications to occur in 38% of patients following pulmonary resections, a frequency that has not significantly changed with time [10, 12, 38]. Because the occurrence of a major complication is a risk factor for early mortality, the overall improvement in mortality suggests an improvement in the management of potentially life-threatening complications, which less frequently result in death [15].

Nonlife-threatening complications are nevertheless important, as the development of complications is associated with both longer hospitalizations and higher costs [39]. The risk factors for mortality listed in Table 6.2 are also risk factors for morbidity. Morbidity risk factors also include active cigarette smoking, significant preoperative functional impairment as indicated by a low Karnofsky index, and the duration of operation time [10, 11, 18, 19, 35, 38, 40, 41]. As with mortality, the extent of operation is a morbidity risk factor, with pneumonectomy having more complications than lobectomy [10, 15]. Complications can generally be categorized as being technical, pulmonary, or cardiovascular in nature, and are discussed in detail in subsequent sections.

Several early reports identified high rates of surgical complications after the use of induction chemotherapy and radiation therapy [42, 43]. Right pneumonectomy seemed particularly hazardous, as one early study reported a significantly increased complication risk and mortality of 23.9% in patients undergoing right pneumonectomy after induction chemotherapy [44]. However, some subsequent reports have shown no significant difference in mortality or morbidity in patients receiving surgery alone versus preoperative chemotherapy followed by surgery for nonsmall cell lung cancer [14, 16, 45]. Right pneumonectomy has also been shown to be relatively safe; a recent study reported an overall mortality of 13.3% after any pneumonectomy following high-dose radiation and concurrent chemotherapy, with a mortality of only 5.6% for

Table 6.3 Perioperative morbidity (patients with at least one complication) for lobectomy and pneumonectomy.

			Lobectomy		*Pneumonectomy*	
Author [Reference]	*Time period*	*Number of institutions*	*Number of patients*	*Morbidity (%)*	*Number of patients*	*Morbidity (%)*
Deslauriers [38]	1988–1989	Multicenter	411	28.2	135	31.9
Kearney [47]	1989–1991	Single center	145	19	46	39
Duque [10]	1993–1994	Multicenter	294	33.3	172	40.1
Harpole [11]	1991–1995	Multicenter	2949	23.8	567	25.7
Siegenthaler [14]	1996–1999	Single center	282	46.1	36	61.1
Perrot [16]	1993–2002	Single center	45	24.4	55	30.9
Allen [12]	1999–2004	Multicenter	766	37	42	27

right pneumonectomy [46]. Despite this conflicting information, it must be recognized that this is a high-risk surgical procedure and that judgment regarding patient selection is important.

Risk assessment

Preoperative pulmonary function tests (PFTs) and room air arterial blood gases are useful in assessing whether a patient can tolerate lung resection [15, 18, 19, 28, 47]. The most useful parameters are the forced expiratory volume in 1 second (FEV_1) and the diffusion capacity to carbon monoxide (DLCO). Although specific absolute preoperative limitations for parameters such as FEV_1 have been quoted for various procedures, the absolute numbers for PFTs are dependent on the patient's body surface area, age, and gender. Therefore, the percent predicted value is much more useful when determining a patient's ability to tolerate lung resection. Further, estimating predicted postoperative percent values is even more useful because the planned extent of resection is taken into account. The predicted postoperative value can be calculated using a formula estimating the decline from the preoperative value based on the number of bronchopulmonary segments to be removed during surgery. Predicted postoperative function can also be determined by using quantitative ventilation–perfusion scans to estimate the contribution of the planned resected lung to overall function. The predicted postoperative DLCO is probably the most useful parameter in assessing risk of postoperative morbidity, pulmonary complications, respiratory failure, and death [39–41, 48, 49–51].

Predicted postoperative values of less than 40% for either FEV_1 or DLCO indicate that patients have increased risk of morbidity and mortality with surgery [51]. In fact, all patients in one study with a predicated postoperative FEV_1 of less than 30% predicted died or required prolonged mechanical ventilation [52]. Although useful, however, PFTs are still only one component of the preoperative assessment. Patients with both low DLCO and FEV_1 have been shown to undergo pneumonectomy and lobectomy with increased but acceptable rates of morbidity and mortality [50, 53, 54]. Patients with marginal predicted postoperative PFTs but with good performance statuses can undergo exercise testing to evaluate oxygen consumption with exercise to further evaluate surgical risk [55]. Patients with maximal oxygen uptake (VO_2max) with exercise testing less than 10–15 mL/kg/min have significant risk for morbidity after lung surgery [56, 57]. High-risk patients who have low DLCO or FEV_1 but VO_2max of greater than 15 mL/kg/min have been shown to tolerate pulmonary resection with minimal mortality and complication rates comparable to those listed in Table 6.3 [54, 58].

Prevention of complications

The optimal strategy of reducing the impact of complications after lobectomy and pneumonectomy is preventing their occurrence. Careful preoperative evaluation and selection of the appropriate surgical procedure has

been linked to improvements in morbidity and mortality [6]. Preoperative workup must include PFTs with diffusion measurements. Quantitative ventilation–perfusion scans and exercise testing are useful in further evaluating patients with marginal pulmonary function, especially those undergoing pneumonectomy. Aggressive preoperative pulmonary rehabilitation should be considered in patients who are marginal surgical candidates. All patients should abstain from cigarette smoking, and all chronic medical conditions should be optimally treated. Patients with poor nutrition should be treated with nutritional supplements or even with enteric feeding tubes if necessary before surgery. Surgeons should have a low threshold to utilize tests such as stress echocardiogram to evaluate patients' cardiac status, with appropriate further workup as indicated.

Complications can also be avoided by appropriate perioperative care [59]. Adequate pain control is required; continuous epidural analgesia is associated with less respiratory complications after pneumonectomy [17]. Intraoperatively, the fraction of inspired oxygen (FIO_2) and airway pressures should be minimized as much as possible, particularly in patients who received induction therapy [2]. Perioperative fluid administration should be limited and combined with diuretic therapy to achieve minimally acceptable urine output. Surgeons should have strict guidelines for routine postoperative care, including maintenance and weaning of mechanical ventilation, glucose control, aggressive physiotherapy and pulmonary toilet, and a strategy to prevent thromboembolic events.

Technical complications

A technical complication directly related to the operation can occur with any structure in the chest when a lobectomy or pneumonectomy is performed (Table 6.4). Table 6.5 lists the incidence of these technical complications reported in several large series. Several of these complications are discussed in the following sections.

Bleeding

Significant bleeding can occur from the pulmonary artery, pulmonary vein, aorta, vena cava, bronchial vessels, or chest wall sites. Life-threatening intraoperative bleeding is rare but can occur, particularly in patients with proximal tumors involving the hilum or with extensive hilar inflammation due to preoperative radiation therapy, infection or inflammatory disease, or previous lung resection. Prevention of significant intraoperative bleeding may be achieved with careful preoperative planning and the practice of gaining proximal control of the pulmonary artery prior to a difficult dissection. Intrapericardial vessel control should be considered in these cases to prevent intraoperative hemorrhage [19]. Hemostasis of the chest wall and pleura is also important, and diligent inspection after resection will significantly minimize overall blood loss. Significant bleeding after lobectomy or pneumonectomy

Table 6.4 Technical complications associated with lobectomy and pneumonectomy.

Bronchopulmonary/pleural	*Bleeding*
Intraoperative respiratory issues	Intraoperative hemorrhage
Hypoxia	Postoperative transfusion
Hypoventilation	Postoperative reexploration
Contralateral pneumothorax	
Lobar torsion	Miscellaneous
Prolonged air leak	Cardiac herniation
Subcutaneous emphysema	Cardiac tamponade
Recurrent pneumothorax requiring chest tube reinsertion	Esophageal injury/mediastinitis
Prolonged chest tube drainage	Thoracic duct injury/chylothorax
Persistent residual pleural space	Intrathoracic nerve injury
Recurrent pleural effusion	Phrenic nerve
Wound complication	Recurrent laryngeal nerve
Superficial wound infection	Spinal cord/dural injury
Bronchopleural fistula	
Empyema	

has as an incidence of 2.5–3.9%; most bleeding can be managed with chest tube drainage and transfusion, though as many as 1.5% of all patients require reexploration for bleeding [10–12, 15].

Prolonged air leak/ chest tube drainage

The most common technical complication after major lung resection is prolonged chest tube duration, typically defined as more than 7 days, due to air leak or excessive fluid drainage. A prolonged peripheral air leak occurs after 6.8–15.6% of major pulmonary resections [10, 12, 60, 61]. Prolonged air leaks do not increase the risk of cardiopulmonary complications, but are associated with prolonged hospitalization and an increased risk of empyema [60, 62, 63].

Table 6.5 Incidence of technical complications after lobectomy and pneumonectomy.

	Lobectomy			*Pneumonectomy*		
	Harpole et al. [11]	*Allen et al. [12]*	*Siegenthaler et al. [14]*	*Harpole et al. [11]*	*Allen et al. [12]*	*Siegenthaler et al. [14]*
Chest tube > 7 days		12			0	
Air leak > 7 days		8			2	
Blood transfusion			8.5			13.9
Bleeding > 4 units	2.9			3		
Hemorrhage		1			2	
Wound complication	2.9		3.5	3.6		11.1
Chylothorax		2			2	
Recurrent nerve injury		1			5	

Prolonged air leaks are usually managed with extended chest tube maintenance, including hospital discharge with a one way valve (Heimlich) on the chest tube if necessary, but sometimes require reoperation. Air leak duration is shortened by placing chest tubes on water seal after a brief period of suction postoperatively if there is not a large air leak or large pneumothorax [64–66]. Patients with emphysematous lungs, a low predicted postoperative FEV_1, and pleural adhesions have an increased risk of prolonged air leak [60, 61]. Prolonged air leaks have also been linked to extensive radical lymphadenectomy as well as upper lobectomy and bilobectomy [60, 61, 67]. Measures to prevent significant air leaks after lobectomy include precise dissection of adhesions, careful handling of the lung during hilar dissection, ensuring adequate bronchial closure, and inspecting the reinflated lung after resection. Intraoperative techniques that can shorten air leak duration include staple line buttress, pleural tenting, and the use of sealants such as fibrin glue, which may be considered in high-risk patients [68–71]. Postoperatively, the use of autologous blood patch to prevent reoperation for persistent air leaks has been demonstrated to be feasible [72].

Chest tube duration can also be prolonged by high fluid output without an accompanying air leak. Patients in this setting must be evaluated for chylothorax. Chest tubes can be removed if there is no air leak and less than 450 ml of nonchylous drainage per day, with only 0.55% risk of requiring readmission due to a symptomatic effusion [73]. Chylous drainage requires chest tube retention. Most cases of chylothorax after pulmonary resection can be managed with a strategy of complete oral intake cessation and total parenteral nutrition [74]. Patients can also be managed with a diet restricted to medium chain triglycerides, though a nasoenteric feeding tube is required because of the poor taste of this diet. Patients with chylous drainage of more than 500 mL during the first 24 hours after oral diet cessation are likely to fail conservative management and should be surgically managed with thoracic duct ligation [74]. The risk of chylothorax is not increased by the use of complete mediastinal lymphadenectomy instead of lymph node sampling [12, 67].

Bronchopleural fistula

Superficial wound infections occur after 1.4–2.7% of major pulmonary resections [10, 11, 19, 38]. More significant wound complications include bronchopleural fistula (BPF), which has an incidence of 0.5–5.1%, and empyema, which has an incidence of 1.1–7.5% [10, 12, 14, 19, 38, 63, 75]. Pneumonectomy has a higher incidence of BPF than lobectomy [75–77]. Postpneumonectomy BPF has a mortality of 25–71%, with aspiration pneumonia a frequent cause of death [75, 76, 78]. Table 6.6 lists other risk factors [63, 76, 77, 79]. Mediastinal lymphadenectomy does not appear to increase the risk of BPF [12, 67]. Intraoperative techniques that lessen BPF risk include avoiding excessive dissection and devascularization of the bronchial stump, minimizing stump length to prevent secretion pooling and subsequent stump breakdown, stump

Table 6.6 Risk factors for bronchopleural fistula after lung resection.

Surgery for benign disease
Low preoperative FEV_1 and DLCO
Right pneumonectomy
Completion pneumonectomy
Preexisting empyema
Previous ipsi-lateral thoracotomy
Residual cancer at the bronchial stump
Malnutrition
Diabetes
Preoperative chemotherapy or radiation therapy
Postoperative mechanical ventilation
Blood transfusions

closure with staples rather than suture, and stump reinforcement with muscle or a pleural flap [19, 63, 79].

BPF should be suspected in patients who develop fever, empyema, aspiration pneumonia, an excessively productive cough, or an increasing air leak or amount of pleural air after lung resection. Presentation may be acute or delayed: the majority of patients present within 3 months postoperatively, most within the first 12 days after surgery [78, 80]. Evaluation should involve bronchoscopy and computed tomography scanning (Figure 6.1). Acute

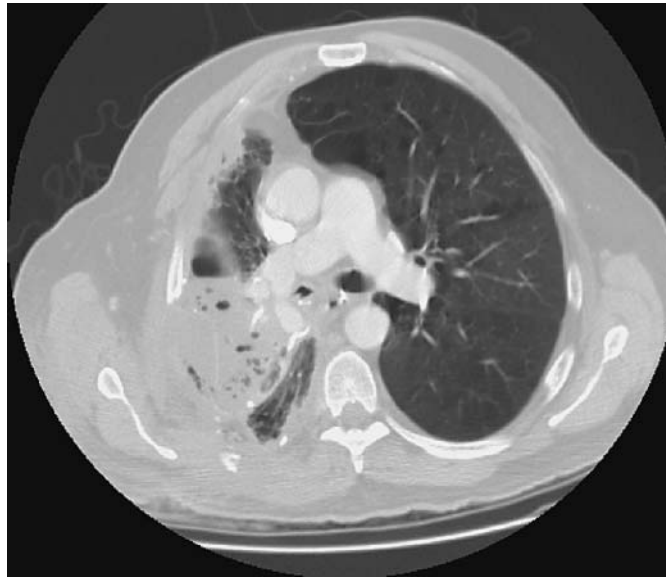

Figure 6.1 A computed tomography scan of the chest demonstrating a right empyema in a patient who had undergone a right upper lobectomy and chest wall resection.

management focuses on controlling life-threatening conditions, including postural drainage with the affected chest positioned down in cases of airway flooding, early pleural drainage to prevent sepsis and aspiration pneumonia, and appropriate antibiotic therapy. Adequate nutrition is paramount to a favorable outcome.

Ultimate successful BPF treatment requires closure of the fistula, adequate drainage, and eventual obliteration of the chest cavity. A major bronchial stump dehiscence requires reexploration for repair and reinforcement with vascularized flaps such as muscle or omentum [80, 81]. Bronchoscopic approaches to close or exclude a BPF with stenting, glues, coils, or sealants may also be attempted but are not as reliable [80, 82]. Management of the chest cavity can involve muscle or omental flaps, open packing, or use of a vacuum-assisted closure device [80, 81, 83]. The Clagett procedure, which involves open pleural drainage, serial dressing changes, operative debridement when needed, and eventual chest closure after filling the pleural cavity with antibiotic solution, has a success rate as high as 81% when treating postpneumonectomy empyema [84]. Recently, the use of tissue flaps has replaced filling the cavity with antibiotic solution.

Mechanical cardiac complications

Echocardiogram should be considered in patients with refractory hypotension after lung resection, as life-threatening mechanical cardiac complications can occur and require emergent reexploration. Pericardial tamponade caused by a bleeding intrapericardial bronchial vessel as well as from a retracted pulmonary vein stump after lobectomy is rare but has been described [85, 86]. Delayed tamponade thought due to ascending aorta injury during mediastinal lymph node dissection has also been described [87]. In addition, cardiac herniation can occur after pneumonectomy if a defect in the pericardium has been made; pericardial repair with fenestrated mesh is required to prevent this complication. Large pericardiotomy or pericardiectomy may be tolerated after left pneumonectomy but should always be repaired after right pneumonectomy to prevent postpneumonectomy syndrome [88].

Pulmonary complications

Pulmonary complications occur in 11–16.7% of patients following major lung resection and are a significant cause of morbidity and mortality [11, 12, 14, 89, 90].

Pneumonia

Most patients have some lung collapse after lung resection, with significant atelectasis occurring in 3.6–6.4% of patients [10, 12, 38, 47]. Aggressive treatment with pain control, pulmonary toilet, and physical therapy is required to prevent a subsequent pneumonia, which has a significant association with mortality [6, 17, 18, 89]. Frequent bronchoscopy and appropriate antibiotic

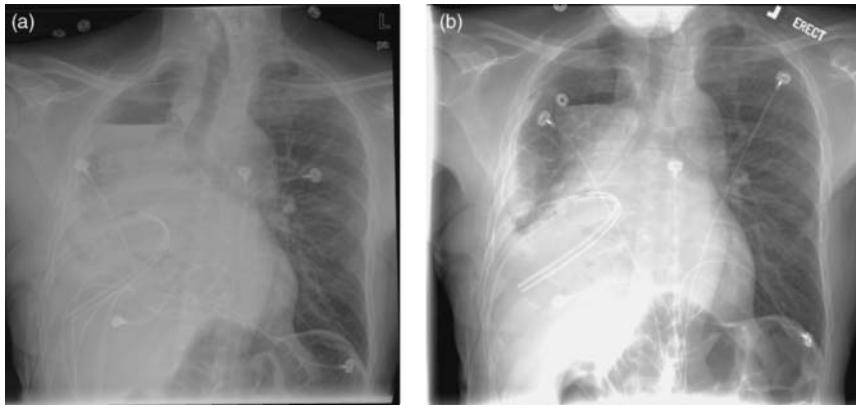

Figure 6.2 Chest x-rays of a patient after right upper lobectomy with (a) extensive right-sided atelectasis and volume loss and (b) significant improvement in right-sided aeration following bronchoscopy.

therapy should be used in patients with poor respiratory efforts, excessive secretions, or radiographic or clinical features worrisome for persistent atelectasis or pneumonia, which complicates 2–11.7% of major lung resections (Figure 6.2 [10–12, 14, 38, 47]). Preoperative smoking cessation will decrease the risk of pneumonia.

Postpneumonectomy pulmonary edema

Postpneumonectomy pulmonary edema (PPE) is a syndrome of rapidly progressive dyspnea and hypoxemia requiring mechanical ventilation, with radiological studies showing diffuse interstitial edema in the remaining lung and no identifiable cause such as heart failure, pulmonary embolism, pneumonia, or BPF [91]. This complication typically develops 2 or 3 days postoperatively, occurs in 1.1–4.5% of patients after pneumonectomy, and has a mortality of 40–100% [17, 19, 36, 91, 92]. Pathogenesis is thought to be an increase in pulmonary capillary hydrostatic pressure due to the remaining lung acutely accommodating the entire cardiac output, a disruption of mediastinal lymphatic drainage, endothelial damage due to higher pulmonary arterial pressures and blood flow, and acute hyperinflation of the remaining lung [91]. Risk factors include an extended pneumonectomy, longer operation, high intraoperative airway pressures, use of an underwater seal pleural drainage system rather than a balanced drainage or no drainage system postoperatively, preoperative radiation, and preoperative perfusion of the remaining lung less than 55% [91, 92]. Perioperative fluid overload and right-sided pneumonectomy have also been identified in some but not all studies as risk factors [17, 19, 28, 36, 91, 92]. The increased risk of PPE with right pneumonectomy could be because the heart and great vessels allow acute mediastinal shift and hyperinflation of the remaining lung more easily compared to left

pneumonectomy [91]. Prophylaxis of this complication should include use of a balanced pleural drainage system and treatment of perioperative hypotension and low urine output with vasopressor or inotropic agents and diuretic therapy with as minimal fluid administration as possible. Treatment is supportive and similar to the treatment described below for respiratory failure.

Respiratory failure

The final pathway of pulmonary complications is respiratory failure that can require prolonged mechanical ventilation. Acute lung injury (ALI) is a syndrome of hypoxemic respiratory failure ($PaO_2/FIO_2 \leq 300$) with bilateral radiological pulmonary infiltrates in the absence of left atrial hypertension or cardiac failure or other identifiable causes (Figure 6.3) [2, 93, 94]. Acute respiratory distress syndrome (ARDS) is the most severe form of ALI, with worse hypoxemia ($PaO_2/FIO_2 \leq 200$) [95]. ALI/ARDS occurs on average 4–6 days following surgery with an incidence of 2.8–7.9% after pneumonectomy and 1.5–3.7% after lobectomy [15, 90, 93, 95]. ALI/ARDS is responsible for most respiratory-related deaths following lung resection and is associated with mortality of 25–50% as well as prolonged hospitalizations [90, 93–96].

Risk factors for ALI/ARDS are listed in Table 6.7 [89, 90, 93, 95–97]. Reports have conflicted on the role of induction chemotherapy and radiation on the development of ALI/ARDS after lung resection. In one study, five of seven patients undergoing pneumonectomy after high-dose chemotherapy and radiation developed diffuse, culture negative pulmonary infiltrates postoperatively [43]. However, other studies have found no change in the incidence of ALI after preoperative chemotherapy [93]. In any case, a safe strategy to minimize the risks of patients after preoperative therapy is to minimize both the FIO_2 and airway pressures as much as possible after anesthesia induction [2].

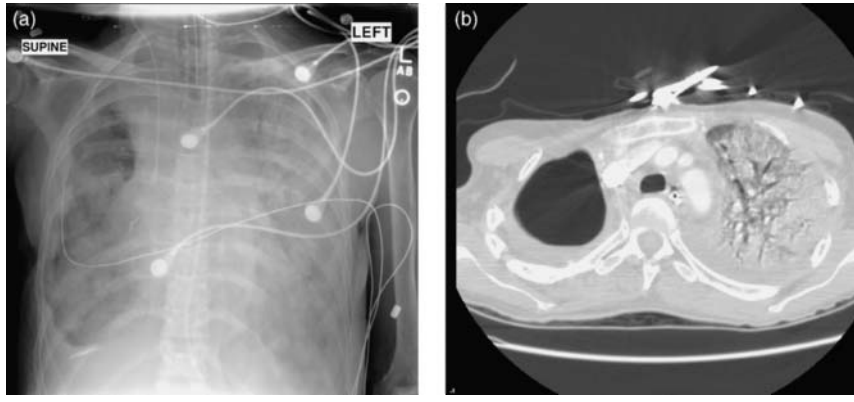

Figure 6.3 (a) Chest x-ray and (b) computed tomography scan demonstrating findings consistent with acute lung injury on the left side in a patient who had undergone completion right pneumonectomy for chronic bronchopleural fistula after previous aspergilloma resection.

Table 6.7 Risk factors for respiratory failure after lobectomy and pneumonectomy.

Age > 60 years
Male gender
Low predicted postoperative DLCO
Excessive perioperative volume administration
Pneumonectomy (especially right pneumonectomy)
Chest wall resections
Preoperative chemotherapy or radiation therapy
Poor nutritional status
Chronic suppurative lung disease
Concurrent cardiac disease
Intraoperative blood loss
Blood transfusions
Reoperation

Intravenous fluids should also be minimized, intraoperatively and postoperatively [96]. One study describes an additional strategy of leaving patients undergoing pneumonectomy after chemotherapy and high-dose radiation therapy on a ventilator for 48 hours with 5 cm positive end-expiratory pressure to maintain positive pressure and reduce the risk of postoperative pulmonary edema [46].

ALI treatment is primarily supportive. Ventilator management strategy advances such as low-tidal-volume ventilation have modestly improved mortality. Randomized controlled studies are needed to determine the efficacy of steroids in the treatment of ALI/ARDS after lung resection. Low dose methylprednisolone used in the early phase of ARDS after thoracic surgery was associated with one small, nonrandomized study with significantly reduced mortality, a result not observed in other studies [93, 97].

Cardiovascular complications

Cardiovascular complications include arrhythmias, myocardial infarction (MI), and thromboembolic events such as deep venous thrombosis (DVT) or pulmonary thromboembolism (PTE). Cerebrovascular events can also be classified as cardiovascular complications and have an incidence of 1.1–2.0% [11, 38].

Arrhythmias

Supraventricular arrhythmias including atrial fibrillation, atrial flutter, and supraventricular tachycardia occur in 4.7–25% of patients after lung resections, most often on the second postoperative day [10, 12, 35, 38, 47, 98–104]. In addition to the lung resection itself, risk factors for arrhythmia include more extensive resections, such as bilobectomy and pneumonectomy, intrapericardial and extrapleural pneumonectomy, right-sided procedures,

age over 60, male gender, history of congestive heart failure, history of previous arrhythmia, preoperative heart rate greater than or equal to 72 beats per minute, and the occurrence of another complication [17, 35, 98, 100, 103–105]. Postoperative arrhythmias are associated with a prolonged hospital stay, higher hospital costs, and increased mortality, as well as an increased occurrence of other complications [18, 35, 99, 102, 103, 105]. Only approximately 15% of patients have persistent arrhythmia on discharge from the hospital; 98% of these patients are free of arrhythmia 2 months after surgery [106].

The precise cause of arrhythmias after anatomic lung resections is unclear and likely multifactorial, involving autonomic denervation and stress-mediated neurohumoral mechanisms [35, 98, 100]. One randomized, double-blind, placebo-controlled study showed that intravenous diltiazem nearly halved the incidence of clinically significant arrhythmias following lobectomy or pneumonectomy [98]. However, it is unclear whether prophylactic treatment of postoperative atrial arrhythmias improves clinical outcomes or shortens hospital stay and whether to employ rate control or rhythm control drugs for this purpose [106]. Prophylactic treatment with digoxin after pneumonectomy did not affect the occurrence of atrial fibrillation in another study [15]. Possible aggravating factors such as respiratory failure or electrolyte imbalance should be corrected before specific drug therapy for acute supraventricular arrhythmias is initiated [106]. Hemodynamically unstable atrial arrhythmias should be treated with urgent cardioversion. Hemodynamically stable patients with arrhythmias less than 24 hours should be treated with intravenous diltiazem or a beta-blocker to control the rate less than 100 beats per minute. Amiodarone should be considered when arrhythmias last more than 24 hours, particularly if any structural heart disease is present [106]. Anticoagulation should be considered when arrhythmias last more than 48 hours to prevent thromboembolic events, which have been observed to occur in 1.7% of patients [98]. However, the benefits of anticoagulation must be weighed against potential bleeding risks.

Myocardial infarction

Coronary artery disease (CAD) and history of prior MI or other chronic heart disease are risk factors for both mortality and morbidity after lung resection. MI occurs in 0.6–1.2% of patients undergoing lung resection. Abnormal preoperative exercise tests and intraoperative hypotension are strongly associated with MI [10, 12, 47, 103]. Patients require careful preoperative assessment and screening. Significant CAD should be addressed before lung resection. Therapeutic options include coronary artery bypass grafting (CABG) or percutaneous coronary intervention (PCI). Prior CABG is associated with significantly fewer postoperative deaths and MIs compared with medically managed coronary disease in patients with CAD undergoing high-risk noncardiac surgery such as thoracic surgery [107]. The American College of Cardiology/American Heart Association (ACC/AHA) guideline for perioperative

cardiovascular evaluation for noncardiac surgery recommends CABG before an elective procedure of high or intermediate risk in patients with prognostic high-risk coronary anatomy [108]. Likewise, the ACC/AHA guidelines recommend that the indications for PCI in the perioperative setting should be similar to those in the ACC/AHA guidelines for use of PCI in general. However, surgery should be delayed by at least 1 week after balloon angioplasty and 4–6 weeks after coronary stenting to allow 4 weeks of dual antiplatelet treatment with clopidogrel and aspirin to prevent in-stent thrombosis [108]. PCI has an advantage over CABG of having a shorter recovery time and therefore less delay of lung surgery. Unfortunately, discontinuing antiplatelet therapy perioperatively to reduce the risk of operative bleeding and to allow safe placement of an epidural regional pain catheter can be associated with adverse myocardial ischemia events after recent coronary stenting [109]. In one study, major lung resection performed within 3 months of coronary stenting was complicated by perioperative in-stent thrombosis in 9% of patients, and occurred in patients who had had 4 weeks of dual antiplatelet therapy after stenting [110].

Deep venous thrombosis and pulmonary thromboembolism

Patients undergoing lung resection have several risk factors for thromboembolic disease, including underlying malignancy, higher age, cigarette smoking, major surgical procedure, and slow postoperative mobilization [111]. Postoperative DVT occurs in 0.7–14% and PTE occurs in 0.4–5.4% of patients after lung resection; PTE was detected in one review in 6% of patients preoperatively [10, 11, 38, 112]. Autopsy findings suggest that central PTE has a postoperative mortality exceeding 80% [113]. Additional thromboembolic risk factors include previous surgery, adenocarcinoma cell type, larger cancer, more advanced cancer staging, and lack of thromboembolic prophylaxis [112]. Although most pulmonary emboli originate from a peripheral DVT, PTE can originate from central sources such as the vena cava after extended resection and the pulmonary artery stump after pneumonectomy [114].

A key issue in management of acute PTE following lung resection is early diagnosis and treatment. PTE can occur despite pharmacological and mechanical prophylaxis and early mobilization, and therefore must always be considered in the suggestive clinical setting [113]. Perioperative subcutaneous heparin reduces, but does not completely remove, the risk of postoperative thromboembolism; so beginning prophylaxis preoperatively and continuing after the operating must be routine [111]. PTE after lung resection often occurs within 1–2 days of surgery, and is typically manifested by sudden respiratory distress accompanied by hypoxia, hypotension, or tachycardia [113, 115]. In one review, almost half of the patients' presentation involved syncope or cardiac arrest [115]. The diagnosis of PTE can be missed because symptoms are mistakenly thought to result from other forms of postoperative respiratory distress such as pneumonia, ALI, chronic obstructive pulmonary disease (COPD) exacerbation, and atelectasis or mucous plugging. Favorable clinical

outcomes have been noted with aggressive diagnosis with enhanced spiral computed tomography scanning [115].

Treatment options for acute PTE include anticoagulation and thrombolysis, vena cava filter placement, mechanical thrombolysis, and thromboembolectomy. All treatments have some risks and should be chosen based on the patient's clinical status [116]. Closely monitored anticoagulation is reasonable with hemodynamically stable patients. Hemodynamic instability requires more aggressive, riskier treatments. Thrombolytics and fibrinolytics have a risk of bleeding, but have been used with dramatic clinical improvements and favorable outcomes following lung resection even when significant bleeding has occurred [111, 115, 116]. Chest tubes must be left in place through the course of either anticoagulation or fibrinolysis so that bleeding can be more easily detected and managed. Surgical embolectomy with extracorporeal circulation has a mortality greater than 40%, is not available at all facilities, and is not useful for peripheral clots, but may be the only life-saving measure for a central PTE and can be successfully utilized in the appropriate clinical setting [111, 113, 114]. Despite prompt treatment, right heart failure can be a cause of death after PTE [113].

Complication by operative approach

Video-assisted thoracic surgery (VATS) utilizes telescopes and video technology to avoid rib spreading. Several large series of the use of VATS for varied lung resections for a variety of benign and malignant conditions have been published since the first description in 1993, though currently only approximately 10–20% of lobectomies done in the United States use VATS [117]. Thoracoscopic anatomic lung resections are equivalent oncologically to conventional open procedures, with similar survival rates found for early stage nonsmall cell lung cancer [118–121]. VATS pulmonary resections have several advantages compared to thoracotomy such as less blood loss, shorter length of chest tube duration and hospital stay, decreased postoperative pain, preserved pulmonary function, shorter recovery time, and improved delivery of adjuvant chemotherapy [117–122]. In addition, thoracoscopic lobectomy is associated with a lower incidence of overall complications [100, 121]. VATS pulmonary resections in patients with poor lung function have also been shown to have low morbidity and mortality [53, 123]. Until recently, thoracoscopic lobectomy was not routinely applied to patients with nonsmall cell lung cancer who had undergone induction chemotherapy or radiation therapy, due to concerns regarding the technical difficulty of hilar dissection in these patients. However, thoracoscopic lobectomy has been shown by a recent series to be a safe strategy in these patients, as patients undergoing lobectomy via thoracoscopy after induction therapy had significantly shorter chest tube duration and length of hospitalization and no difference in frequency of postoperative complications, including 30-day mortality, hemorrhage, pneumonia, or respiratory failure, when compared with conventional thoracotomy [124]. The

only absolute contraindication to VATS resection is the inability of the patient to tolerate single-lung ventilation.

Table 6.8 lists the complication rates as reported in several large series of VATS resections [118–120]. Persistent air leak is generally the most common complication, along with atrial arrhythmias and pneumonia. In order to allow comparison of complications of VATS resections to resections via thoracotomy, Table 6.8 also lists the complication incidences reported by Allen *et al*. [12] from prospectively collected data of 1023 current, multi-institutional patients who underwent a major pulmonary resection with either lymph node sampling or mediastinal lymph node dissection. The pulmonary resections in this series were by means of thoracotomy in 90% of patients, with 6% via VATS, and via a combined approach in 4%. Comparison of the Allen series with the other series listed in Table 6.8 shows that complications with thoracoscopic resection are generally comparable to resection via thoracotomy. Perioperative mortality was also comparable; the perioperative mortality in the series reported by Allen was 1.37%, while the perioperative mortality reported by Onaitis, Rovario, and McKenna was 1.2, 0.7, and 0.8%, respectively. There were no intraoperative deaths in the

Table 6.8 Postoperative complications after major pulmonary resections; the series reported by McKenna, Onaitis, and Rovario reports on VATS resections, while the series by Allen reports on 1023 patients in which thoracotomy was utilized 90% of the time.

	Series			
Complication	*McKenna et al. [119] (1100 patients)*	*Onaitis et al. [118] (500 patients)*	*Roviaro et al. [120] (259 patients)*	*Allen et al. [12] (1023 patients)*
Technical				
Hemorrhage: transfusion	4.1			2.4
Hemorrhage: reoperation	0	0.2	0.8	1.5
Chest tube in > 7 days	1.3			11.5
Prolonged air leak	5.1	4	7.7	7.6
Chylothorax				1.3
Bronchopleural fistulas	0.3		0.4	0.5
Recurrent nerve injury			0.4	0.7
Empyema	0.4			1.1
Subcutaneous air	1.1	0.8		
Pulmonary				
ARDS	0.1			0.7
Respiratory failure		1.2	0.4	5.5
Pneumonia	1.2	5		2.5
Atelectasis	0.2			6.4
Cardiac				
Atrial arrhythmia	2.9	10		14.4
Myocardial infarction	0.9	0.4		0.9
Pericarditis	0.1			

All complication rates are reported as percentages.

VATS series. Review of Table 6.8 suggests that atrial arrhythmias, one of the most common complications following noncardiac thoracic surgery, may occur less frequently with VATS compared to thoracotomy. However, a recent case-control study found that atrial fibrillation rates occurred with equal frequency in patients undergoing lobectomy by either VATS or thoracotomy [100]. Prophylaxis regimens against atrial fibrillation used after thoracotomy should therefore also be considered for VATS resections.

Video equipment malfunctions are unique to VATS. Surgeons must be prepared to prevent complications occurring as a result of video equipment failures. The operating room team must have someone familiar with the setup of the camera, light source, and monitors present at all times, as well as the ability to obtain backup equipment or contact a video equipment expert in the event of equipment failure. In addition, the instruments needed for thoracotomy must always be immediately available during thoracoscopic surgeries, in case conversion to thoracotomy is needed due to nonrecoverable video equipment problems or to avoid intraoperative complications or compromise from an oncologic standpoint. In the event of significant bleeding from a major pulmonary vein or artery branch injury that can not be repaired thoracoscopically, the source of bleeding can usually be identified and controlled with a thoracoscopic instrument to allow controlled and stable conversion to thoracotomy. Conversion sometimes is also required in the event of stapler malfunction or when an unexpected oncologic condition such as chest wall invasion or the need for a sleeve resection is encountered during thoracoscopy. Although conversion to thoracotomy should always be considered appropriate to manage unexpected situations, conversion rates are as low as 1.6–2.5% in large series by experienced thoracoscopic surgeons [118, 119].

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CHAPTER 7

Complications of Tracheobronchial Resection

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Bronchoplasty

Techniques have been developed to allow sleeve resection of any lobe of the lung. These techniques allow surgery for individuals who could not tolerate more extensive operations and an improved quality of life due to the preservation of functioning lung parenchyma. For these reasons, practicing thoracic surgeons should be familiar with the technical details of the operation. The technical demands of bronchoplasty are such that there is an increased risk of complications compared to standard lobectomy. These can be minimized by strict attention to technical details. True of all surgery, avoidance of complications begins with patient selection and with an intimate knowledge of the tenets and potential pitfalls of a particular operation. Complications do occur, however, and one should be familiar with their presentation and management possibilities.

Indications for sleeve lobectomy

Knowing the indications for bronchoplasty will help in patient selection and improve results. The most common indication for sleeve lobectomy is the presence of a benign or malignant neoplasm originating at the origin of a lobar bronchus. It is the rare neoplasm that can be managed by endoscopic methods with the expectation of cure. Hamartoma and papilloma may be the exceptions. One should not be tempted to try laser ablation or removal of benign or low-grade neoplasms. The biology of these tumors is such that they always involve the bronchial wall deeply enough that complete removal or obliteration is impossible. Extensive lasering can lead to bronchial stricturing and also to bronchial perforation, inflammation and growth of the neoplasm, possibly precluding a future bronchoplastic procedure.

There are other conditions that may be amenable to bronchoplastic techniques. At the time of thoracotomy, the origin of the bronchus may be found

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to be involved with malignant lymph nodes, or positive frozen section margins may document direct extension of the primary neoplasm. These are conditions not identifiable by bronchoscopy and underscore the need for thoracic surgeons to be familiar with bronchoplastic techniques. Other indications are post-traumatic, postinflammatory, and postsurgical strictures, where preservation of as much lung parenchyma as possible does not compromise the goals of the operation.

Evaluation of patients for bronchoplastic procedures

Preoperative assessment of patients is important to determine the timing and appropriateness of surgery as well as the limits of resection. The advanced knowledge provided by thorough evaluation will help in planning the operation and improving overall results. As always, a general medical evaluation should be performed to determine the patient's ability to tolerate the procedure. In the case of pulmonary resection, it is essential to perform a physiologic evaluation of a patient's pulmonary function and reserve. This includes an assessment of the patient's functional capacity as well as exercise testing, such as stair climbing in a supervised setting, along with standard spirometry. In cases where there is concern of marginal functional status, further investigation should be undertaken with quantitative ventilation/perfusion scans and cardiopulmonary exercise testing to measure maximal oxygen consumption $(VO_2)_{max}$ [1]. Such investigation will help determine whether a bronchoplastic procedure is the only option if anatomical findings are unfavorable at thoracotomy. These tests are obtained routinely for all patients if there is any question about their ability to withstand the alternative to sleeve lobectomy, that is, pneumonectomy.

The operating surgeon should perform bronchoscopy. One should never rely on the observation of others to assess the suitability of a patient for a possible bronchoplastic procedure. The bronchoscopy should reveal the origin of the pathology, the extent of involvement, and the quality of the bronchial mucosa. The use of flexible bronchoscopes allows, in almost every circumstance, the evaluation of the bronchus distal to the pathology. Even neoplasms that protrude into the lumen of the main bronchus and seemingly occlude the entire bronchus can usually be bypassed by carefully insinuating the tip of the bronchoscope around the periphery of the neoplasm. This can be useful to determine the extent of the tumor in planning the correct operation before thoracotomy. It can be sorted out during the planned resection by bronchotomy, but this is not ideal and may compromise the procedure. It is important to assess the bronchial mucosa for inflammatory changes as well. One should not attempt bronchoplastic procedures with mucosa that is actively inflamed.

The radiological assessment of patients being considered for possible bronchoplastic procedures is also valuable. Standard linear tomograms were quite useful in assessing bronchial pathology, but they have become virtually impossible to obtain. Computed axial tomograms (CT) and spiral CT scans, with their increased resolution and 3D reconstructions, have supplanted

linear tomograms. They are superior for the determination of extraluminal involvement and the presence of enlarged lymph nodes.

For malignant lesions, mediastinoscopy should be performed to assess involvement of mediastinal lymph nodes. Positive nodes influence the choice of operation and the need for adjuvant therapy. Mediastinoscopy allows some assessment of the proximal mainstem bronchus as well as the main pulmonary artery. Combining these findings with bronchoscopic findings and pulmonary function tests will guide one in determining the suitability of bronchoplasty. Mediastinoscopy should be performed at the time of thoracotomy or as close to it as possible. The resultant scarring that inevitably follows the procedure can compromise the mobility of the airway, the dissection of the bronchus, and can create confusion as to what is scarring and what is neoplasm.

Postobstructive pneumonia is common in patients with obstructing neoplasms [2]. It is preferable to try to resolve this before the bronchoplastic procedure. In addition to appropriate intravenous antibiotics and chest physiotherapy, aspiration bronchoscopy is invaluable. This may need to be repeated multiple times to clear the secretions and reduce the inflammation. In some cases, ''core-out'' of the neoplasm should be done to open the obstruction. Balanced against this goal is the risk of hemorrhage from relatively vascular neoplasms such as carcinoids. In this situation, multiple aspiration bronchoscopies may be preferable. Most other neoplasms can be safely trimmed back endobronchially to recannalize the airway with minimal risk of bleeding [3]. A few days spent relieving postobstructive pneumonia is time well spent. The general risk of sepsis is reduced, purulent secretions diminished and inflammation of the bronchial mucosa reduced. All of these diminish the risk of postoperative complications.

Anesthetic considerations

It is important to perform these operations under optimal conditions. The management of the airway is critical to the safe conduct of the operation. The use of a double-lumen endotracheal tube is preferable. Bronchial blockers are alternative solutions, but they do not provide as much protection of the opposite lung from spilled secretions and, in general, are only a consideration for left-sided bronchoplastic procedures. Placement of double-lumen tubes should be done with the aid of a flexible bronchoscope through the tube. This minimizes trauma to any neoplasm, reduces the risk of bleeding, and guarantees proper placement. The actual anesthetic should allow for extubation in the operating room at the conclusion of the operation. It is preferable to have these patients extubated rather than mechanically ventilated which hampers the clearance of secretions and subjects the new anastomosis to positive pressures. Maximal pain control helps to allow vigorous coughing and to thereby avoid complications from sputum retention. Epidural analgesia in thoracotomy patients, when properly administered, will facilitate the clearing of these secretions by reducing the patient's difficulty with coughing, deep

breathing and activity—all of which are paramount to achieving adequate pulmonary toilet.

Surgical technique

Success depends upon precise attention to technical details. Gentle handling of the tissues, preservation of the blood supply, and avoidance of tension on the anastomosis are essential. The technical details are the same as for standard lobectomy until the bronchus is reached. At this point, avoiding devascularization of the bronchus is important for bronchial healing. A balance must be achieved in lymph node dissection as well, because node dissection often interferes with bronchial blood supply. Sharp transection of the bronchus should be accomplished with minimal trauma to the remaining ends of the bronchus. To avoid confusion for the pathologist, it is best to submit a separate sliver of bronchus from each end for histological review. This practice minimizes sampling mistakes by the pathologist.

Tension on any bronchial anastomosis must be avoided. When long segments of the main bronchus are included in the resection, it may be necessary to perform an inferior pericardial release. Release is accomplished by making a U-shaped incision in the pericardium beneath the inferior pulmonary vein (Figure 7.1). This incision gives enough mobility in all but extreme situations. An incision of the pericardium to completely encircle the hilar vessels can be

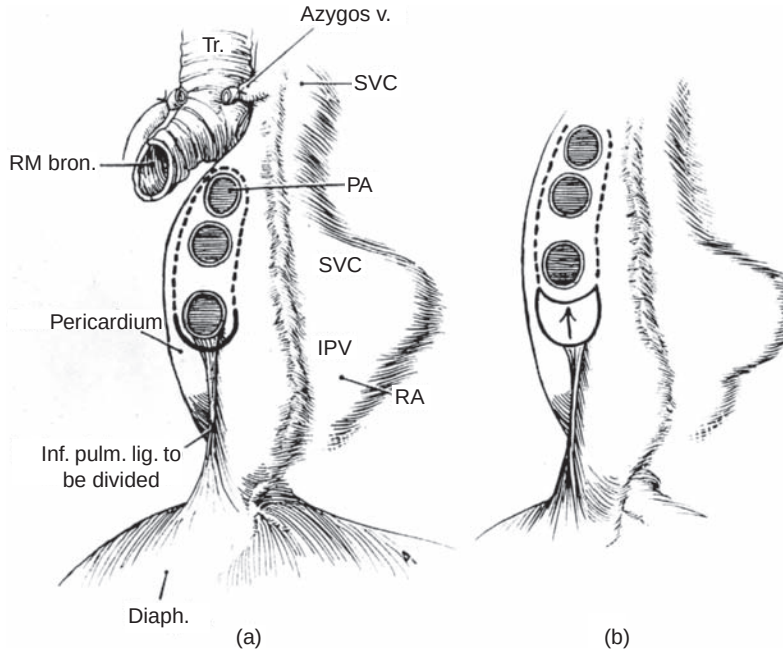

Figure 7.1 Inferior pericardial release (solid line). Encircling pericardial release (dashed line) for maximal mobility.

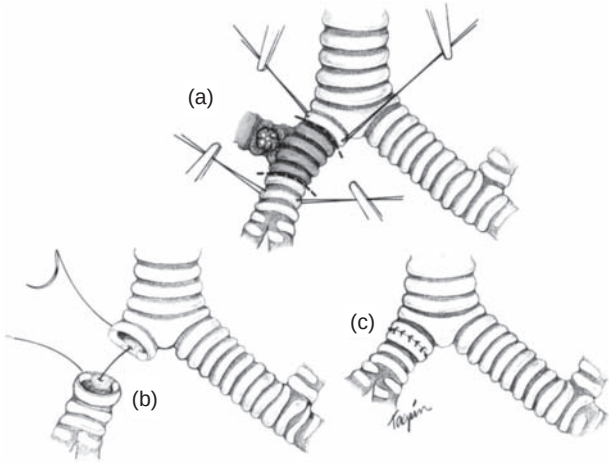

Figure 7.2 Right upper lobe sleeve resection. (a) Resection of right upper lobe with portion of right mainstem bronchus; (b) placement of interrupted absorbable sutures; (c) anastomosis of bronchus intermedius with right mainstem bronchus.

used in this circumstance for maximal mobility. Two full thickness 2-0 vicryl traction sutures are placed in the proximal and distal end of the bronchus in the mid-lateral position. These sutures are helpful in approximating the bronchi and reducing tension (Figure 7.2a). This helps to determine proper spacing of and, when tying, to reduce tension on the individual anastomotic sutures. These stay-sutures are placed 3–4 mm from the end of the bronchus and should always be around a cartilaginous ring rather than in the membranous wall. They are tied before the individual anastomotic sutures are tied and they are left in place. Absorbable sutures eliminate the granuloma formation so common with nonabsorbable sutures.

Anastomotic sutures are carefully spaced and placed 3–4 mm from the cut end of the bronchus (Figure 7.2b). The sutures are 4-0 Vicryl. Each suture is clipped to the drapes and tied in reverse order of placement (Figure 7.2c). The open technique allows precise placement of sutures. Size discrepancies usually exist between the proximal and distal ends of the bronchus. Tailoring of either end is avoided in most circumstances, instead relying on proper spacing of sutures to make up for any size difference. Some telescoping inevitably occurs, but this has not been a problem in our experience. Occasionally, when the entire right main bronchus, upper lobe, middle lobe, and bronchus intermedius are removed, the size discrepancy is too great and the proximal bronchus must be tailored to reduce the circumference. Narrowing of the bronchus inevitably creates a T intersection in the anastomosis. One must pay meticulous attention to detail to avoid creating a potential area for a fistula. Once all sutures have been placed, the traction sutures are tied bringing the two ends together.

At the completion of the anastomosis, the operative field is flooded with saline and the lung ventilated. Any air leaks should be repaired, even if it means taking down and redoing the anastomosis, to avoid a fistula. Flexible bronchoscopy is done at this point to be certain that there is proper alignment, patency of lobar and segmental bronchi, and no loose anastomotic sutures. All of these problems are best identified and corrected at this point rather than identifying them postoperatively. Once the integrity of the anastomosis has been confirmed, a pedicled flap of pleura or pericardial fat is developed and passed around the anastomosis. This may aid in healing and separates the bronchus from the nearby pulmonary artery.

Special mention should be made of patients who are on steroids, have an active infectious pulmonary process, or who have had prior irradiation over 1 year before surgery. These factors impair bronchial healing, increasing the risk of bronchoplastic procedures, and potentially preclude surgery. When bronchoplasty is performed in these situations, a more robust muscle flap is indicated. A pedicled muscle flap, intercostal muscle, serratus anterior or latissimus dorsus, is the choice for buttressing the anastomosis. In the specific case of an intercostal muscle flap, if the anastomosis is to be wrapped circumferentially, the periostium must be stripped to avoid the formation of a ring of reconstituted bone that may constrict the bronchus [4]. A pedicled omental flap passed through a substernal tunnel may also be used.

If postoperative irradiation is to be given, it is best to wait 4–6 weeks after surgery. A bronchoscopy should be done prior to initiation of radiation therapy to be certain that adequate healing has taken place.

Management of complications

The most common postoperative complication is sputum retention and atelectasis. Proper antibiotic selection, chest physiotherapy, and pain control are very important in the management of this problem. In addition to nasotracheal aspiration, bronchoscopy, with irrigation of the distal airway, should be used liberally.

Bronchoscopy should be done in the postoperative period to examine the anastomosis to ascertain whether or not normal healing is taking place. If the bronchial mucosa is ischemic but intact, a bronchoscopy should be done every few days to monitor the situation. If the anastomosis appears to remain intact, late stenosis may develop. This may take the form of a fibrotic stricture or exuberant granulations. Excessive granulation tissue may be debrided or lasered. A fibrotic stricture may be amenable to repeat dilations with balloon dilators or woven bougies through a rigid bronchoscope. One may need to repeat these procedures to maintain patency and avoid postobstructive pneumonia or atelectasis of the lung. It is possible that a partial stenosis will result without clinical consequence. However, if recurrent infection, atelectasis or shortness of breath become troublesome, intervention is necessary. Bronchial stents have limited application for stenosis following sleeve lobectomy because of the short length of distal bronchus available. A stent would be

difficult to seat, maintain patency, and avoid granulation formation. Before reoperation, sufficient time should be allowed for resolution of postoperative inflammation and fibrosis. A period of 3 months is ideal, but may not be feasible. A redo bronchoplastic procedure may be impossible, and completion pneumonectomy may be inevitable. The bronchial stump may be difficult to close because of rigidity or short length. A difficult bronchial stump of this nature should be reinforced with a pedicled muscle flap.

If bronchoscopic inspection of the anastomosis reveals dehiscence, partial separation, or frank necrosis, surgical intervention is mandatory. Completion pneumonectomy should be performed in most cases. Attempts to redo or repair the anastomosis are generally futile and very risky. If completion pneumonectomy is not an option because of certain respiratory insufficiency and the process is caught early enough, an attempted repair can be entertained. Conditions would have to be ideal (no gross infection, no involvement of the pulmonary artery), and thorough debridement of devitalized tissues, with no anastomotic tension, is essential. Wrapping the anastomosis with pedicled omentum or healthy muscle provides the greatest chance of success without fatal complications.

Development of a bronchopleural fistula is a devastating postoperative complication. If a bronchopleural fistula is suspected, a bronchoscopy should be done to evaluate the anastomosis. If a small defect is identified, conservative management should be tried initially. This includes proper antibiotics, complete drainage, and possible irrigation to help evacuate infected material. A CT scan with contrast is done to be certain that all infected material is drained and no residual collection remains. Such long-term drainage may allow for eventual closure. However, if the fistula cannot be controlled, surgical exploration should be done to address the problem more definitively. This may be the only way to avoid a fatal bronchovascular fistula. If the fistula fails to close after adequate drainage and sufficient time (minimum 3 months), one may consider attempted repair. Debridement, closure with absorbable sutures, and pedicled omental or muscle flap buttress should be done. The development of a bronchopleural fistula may result in late bronchial stenosis as well. This may influence the management of this problem and preclude local repair. If repair of the anastomosis is deemed impossible, completion pneumonectomy becomes necessary.

A related complication following a bronchoplastic procedure is the dreaded development of a bronchovascular fistula. This results from anastomotic breakdown and erosion into the adjacent pulmonary artery. This problem is clearly one that is best managed by avoiding the problem altogether, and is a compelling reason to consider wrapping every anastomosis with viable pedicled tissue of some sort to buttress and separate the anastomosis from the vascular structures. Most bronchovascular fistulas have a ''herald bleed'' of a significant amount of blood. Any episode of hemoptysis after a bronchoplastic procedure should immediately be evaluated. Bronchoscopic findings may

be subtle, with only an area of granulation tissue, or obvious, with frank dehiscence. If a bronchovascular fistula is confirmed, immediate surgical intervention is warranted. Delay may be fatal. It is unlikely that anything other than completion pneumonectomy is possible in this circumstance. It is essential to gain proximal control of the pulmonary artery before exposing the fistula. The mainstem bronchial stump may be difficult to close and should be buttressed with a pedicled muscle flap in every case. Because of the likelihood of contamination of the pleural space, copious irrigation with saline and an antibiotic solution is done. If gross contamination of the pleural space exists, consideration should be given to postoperative antibiotic irrigation of the pleural space and open drainage. A Clagett procedure can then be done at a later date. If reduced lung function absolutely precludes completion pneumonectomy, repair can be attempted. This requires considerable judgment. The devitalized tissue must be resected and the defect repaired using 4-0 vicryl sutures. A muscle flap should be utilized to separate the repaired area from the pulmonary artery. A stricture will eventually develop, but can be addressed as long as infection is controlled.

Local recurrence of tumor can be a late complication of sleeve lobectomy. Because of this potential, surveillance bronchoscopy twice a year is warranted in these patients. Early detection may afford an opportunity for re-resection in some cases.

Outcomes

The favorable results associated with bronchoplastic procedures have altered the management of both benign lesions and malignancies associated with the airways. The most comprehensive review of complications and early mortality after sleeve resections was provided by Tedder and colleagues [5]. In their review of 1915 patients, the perioperative mortality was 7.5%. Complication rates included local recurrence in 10.3%, pneumonia and atelectasis in 6.7% and 5.4%, respectively, stricture in 5.0%, and a range of 2.6–3.5% occurrence of bronchopleural fistula, empyema, and bronchovascular fistulas (Table 7.1). Our series at Massachusetts General Hospital, suggests better quality of life and survival (greater than 90% 5-year survival for benign diseases and approximately 50% for malignancies) with sleeve resections as compared with pneumonectomy. We have had very few complications and an acceptable mortality rate in over 200 bronchoplastic procedures for benign and malignant disease [6]. The operative mortality in 100 patients with benign low-grade neoplasms was 2%, and 4% in 72 patients with malignant neoplasms. The deaths in the malignant group occurred in patients with compromised pulmonary function. Early and late morbidity was quite low in both groups of patients as well. There were no bronchovascular fistulas, one empyema, three bronchial stenoses, and one dehiscence. Survival for malignant neoplasms, as reported in the literature, ranges between 45% and 55%, similar to that in pneumonectomy patients. Because of these findings, and findings reported in other series,

Table 7.1 Complications and early mortality in 1915 patients after bronchoplastic procedures for malignancy.

Complication	*No. of patients*	*Incidence (%)*
Local recurrence	110/1064	10.3
Thirty-day mortality	143/1915	7.5
Pneumonia	32/481	6.7
Atelectasis	33/614	5.4
Benign stricture/stenosis	48/966	5.0
Bronchopleural fistula	42/1186	3.5
Empyema	17/599	2.8
Bronchovascular fistula	16/615	2.6
Pulmonary embolism	13/672	1.9

Source: Reprinted with permission from the Society of Thoracic Surgeons [5] .

sleeve resection has become the procedure of choice, not only for patients with compromised pulmonary function, but also for any anatomically suitable pathologic processes [2, 7, 8].

Bronchoplasty is a procedure of which all thoracic surgeons should be knowledgeable. Strict attention to patient selection, technical details, and postoperative care should allow the procedure to be done safely with low operative morbidity and mortality, avoiding most potential complications. Early identification and aggressive management of complications should allow for success and avoidance of most fatal outcomes.

Tracheal resection and reconstruction

The goals of tracheal surgery are to resect the diseased segment of trachea and perform an end-to-end reconstruction with a tension-free anastomosis [9]. As with bronchoplastic procedures, an understanding of the indications for surgery and of the risk factors associated with adverse outcomes will guide proper patient selection. Subsequently, knowledge of the tracheal anatomy and surgical techniques coupled with proper airway management will improve the chance of success and minimize the risk of complications, thus ensuring a patent airway and preserved voice, obviating the need for permanent tracheostomy.

Patient selection, risk factors, and preoperative evaluation

The most common indication for surgical resection remains postintubation stenosis following prolonged mechanical ventilation. This is usually a circumferential stenosis resulting from cuff injury, despite the advent of low pressure, large volume cuffs. Tracheo–esophageal fistulas, tracheal malacia, and subglottic stenosis involving the larynx may also occur in this setting, the latter being particularly difficult to manage and possibly irreparable [10].

Neoplasms represent the second most common indication for tracheal resection in adults. Other less common indications include post-traumatic sequelae, inflammatory/ infectious etiologies, idiopathic stenoses, and failed primary repair.

Preoperative assessment of patients with tracheal pathology should focus on a number of factors including: (i) patient comorbidities and characteristics such as body habitus, age, and neck anatomy; (ii) the location and extent of disease; (iii) and the presence of various risk factors associated with adverse outcomes.

Up to approximately one half of the adult trachea may be resected with various release maneuvers [11]. The actual extent of resection varies considerably, between that for a relatively young individual with a long, supple neck and that of an older, kyphotic patient with limited mobility of the neck.

Unrecognized glottic incompetence from a pre-existing condition, predisposing to aspiration or airway obstruction, can be compounded by tracheal resection and reconstruction. Evidence for cord dysfunction should be sought out and investigated prior to consideration of operation.

In a retrospective analysis of 901 patients undergoing tracheal resection, Wright *et al*. identified diabetes, reoperation, longer resections, young age (pediatric patients), presence of tracheostomy prior to resection, and laryngotracheal resection as risk factors for anastomotic failure. The increased risk associated with the impaired wound healing in diabetes, the more extensive nature of the dissection associated with reoperation, tracheostomy, and longer, higher resections are somewhat intuitive. It is thought that children tolerate anastomotic tension less well than adults [12].

Inhalation/burn injuries to the trachea initially are manifested by severe tracheobronchitis with mucosal sloughing potentially leading to strictures of the upper airway. Specific to this type of injury, there is an extended period of time when the trachea is prone to hypertrophic scar formation. For this reason, while the optimal time for reconstruction of such stenoses remains undetermined, initial management with prolonged use of T-tubes is often beneficial. This will allow a window of opportunity for the inflammation to subside, and may even result in recovery of a functional airway and voice without surgery. In those patients who require surgical intervention, delayed resection and reconstruction will increase the likelihood of a successful outcome [13]. Previous radiation is also associated with poor wound healing [14]. The fibrosing process inhibits capillary proliferation, mucosal blood flow, and migration of fibroblasts into the wound, all of which are critical to the reparative response in healing anastomoses. In patients with prior radiation to the trachea or mediastinum, in whom tracheal resection is contemplated, the use of pedicled omentum or nonirradiated muscle flaps should be used to improve success [15].

Tracheal resection is generally inadvisable in patients with certain comorbidities. The classic examples would be patients with severe myasthenia

gravis, or marginal respiratory status from other underlying conditions, with histories of frequent hospitalizations and reintubations. Massively obese patients and those with severe sleep apnea must be carefully considered. Quadriplegic patients may have sufficiently compromised chest wall mechanics and difficulty with secretions and therefore must be carefully selected as potential candidates. All of these high-risk patients are best managed with a permanent tracheostomy or T-tube in most instances.

Delay of surgery may be advisable in a few specific situations. Not infrequently, patients present on high dose steroids, most often as therapy for an underlying immunologic disease process, misguided treatment for presumed asthma, or as treatment for a severely inflamed trachea. Such patients must be weaned and a minimum of 4 weeks should be allowed for normal healing mechanisms to return. Tracheal dilations may be required while waiting. Active, florid inflammation is a warning to judiciously delay surgery until after the inflammation has had a chance to subside. Time and patience on the part of the surgeon is of the essence.

Success is achievable following failed reconstructions but requires careful patient selection. Tracheal resection and reconstruction is notably worse in patients with prior attempts at resection. This is due to a combination of factors: a relatively small amount of normal available trachea, a more difficult dissection of fused tissue planes, and a greater risk of compromising the recurrent laryngeal nerves and blood supply. The best chance of success is with the initial operation and this should be performed by those with experience and intimate knowledge of the procedure and its potential pitfalls. Adherence to the basic principles of tracheal reconstruction, including avoidance of anastomotic tension, preservation of the tracheal blood supply, and meticulous technique will reduce the failure rate at the initial procedure [9].

Thorough preoperative evaluation is invaluable for optimal operative planning. Simple radiological studies will help assess the extent of airway involvement. Soft tissue X-rays of the neck and linear tomograms give excellent detail of the pathology. CT, spiral CT scans, and magnetic resonance images are newer, alternative options.

The most important assessment is bronchoscopy. Bronchoscopy is best done in the operating room where emergency rigid bronchoscopy can be done to manage critical airway stenosis if it develops. Preliminary inspection with a flexible bronchoscopy should be limited to inspection of the area proximal to the stenosis, as manipulation of the stenosis may lead to secretions, edema, or bleeding which may precipitate critical airway stenosis. The rigid bronchoscope is a more useful instrument. It is safer, allowing one to ventilate and control the airway while carefully inspecting the tracheal pathology. It can be used to dilate a critical stenosis if necessary. The length and precise location of involvement should be carefully measured, as well as the total length of airway and amount of uninvolved airway. It is also important to assess the

trachea for the presence of inflammation which is common in many conditions involving the trachea.

Airway protection and management

Along with proper patient selection and evaluation, airway management is essential for successful care of tracheal pathology. The initial presentation of a patient with tracheal stenosis is rarely an emergency. Maintenance of the patient in the upright position and the application of cool, humidified oxygen will often stabilize the patient and allow airway assessment under controlled circumstances. For patients with evidence of edema or inflammation, inhaled racemic epinephrine or a short course of steroids (24–48 hours) may be beneficial. Heliox, a mixture of 80% oxygen and 20% helium, may be helpful in the acute setting, because of its reduced viscosity.

Ultimately, the patient is best managed in the operating room where experienced anesthesiologists, trained OR staff, pediatric and adult rigid bronchoscopes, and tracheostomy kits are all readily available. Anesthesia for tracheal evaluation and treatment is a cooperative effort between anesthesiology and surgery [16]. The rigid bronchoscope is the most important instrument in the operating room, serving dual roles, as a conduit through which ventilation can proceed, and as a tool to evaluate the trachea and dilate tight strictures.

Ideal anesthetic management has as its goals smooth, controlled induction and maintenance of adequate ventilation during the procedure. This is achieved by a balance of spontaneous ventilation and deeper anesthesia once the airway has been secured using a combination of short-acting agents. Once an adequate level of anesthesia has been achieved, an adult rigid bronchoscope is carefully inserted into the proximal airway to visualize the area of stenosis. A pediatric flexible bronchoscope can be inserted through the rigid bronchoscope to inspect the entire length of the stenosis. Tight strictures can be serially dilated with pediatric rigid bronchoscopes (3.5–7 mm diameters). Passage of the small rigid bronchoscopes is facilitated by a laryngoscope to expose the epiglottis and a 2-mm rigid telescope positioned within the bronchoscope to visualize the airway. This is done with gentle pressure under direct vision. It is almost always possible to dilate strictures to a 7-mm rigid bronchoscope, which is a sufficient lumen to maintain a patent airway in most patients for days to weeks following dilation. Tumors may also be ''cored out'' using a rigid bronchoscope. If an adequate airway cannot be established, either a tracheostomy or T-tube placement can be performed through the most damaged portion of the airway to preserve as much viable trachea as possible for future reconstruction. Covered wire or silicone stents may be placed in limited situations. If left too long, they may extend the area of stenosis by inducing inflammation and granulation tissue.

The increasing use of airway stents in recent years has been a double-edged sword. Airway stents are indicated for benign and malignant strictures in

patients with limited life expectance or in patients whose lesions are not suitable for surgical resection. Metal/wire stents have drawbacks, including risk of migration, deformation, or erosion and generally have poor results in the setting of inflammation [17, 18]. Uncovered metal stents tend to become incorporated into the walls of the airway, inciting more inflammation and granulation, making them difficult if not impossible to remove, and compromising longer areas of respiratory mucosa [19]. For these reasons, the general consensus is to avoid placement of such stents in airways that may be considered for resection and reconstruction so as not to convert a potentially resectable lesion into an unresectable one. If temporary or long-term restoration of airway continuity is required, silicon T-tubes are better tolerated, nonreactive, and easily removable [20]. They are therefore preferable.

Surgical technique

The majority of tracheal resections can be performed through a cervical collar incision. A small partial upper sternotomy, extending just beyond the angle of Louis, gives additional exposure of the distal trachea. The important anatomical considerations are the recurrent laryngeal nerves located in the tracheo–esophageal groove, the esophagus posteriorly, and the segmental blood supply that enters the trachea in the mid-lateral position [21–23]. Initial circumferential dissection is kept on the tracheal wall. The tracheal blood supply originates from the inferior thyroid arteries and the bronchial circulation, the branches entering the posterolateral margin of the trachea in a segmental fashion. Therefore, it is important to avoid circumferential mobilization of the trachea beyond 1–2 cm from the point of transection. No attempt is made to identify the recurrent nerves, since they are often embedded in scar and easily injured if there is an attempt to identify them. The trachea should be encircled just proximal or distal to the area of stenosis. This allows dissection in an area with minimal scarring which reduces the risk of injury to the esophagus. A tape is passed around the trachea to provide traction and elevation.

We prefer to ventilate patients during resection with a sterile endotracheal tube on the operative field inserted into the distal airway connected to sterile tubing, which is passed off the operative field to the anesthesiologists (Figure 7.3a). This enables the endotracheal tube to be removed, allowing for careful inspection of the airway and precise placement of sutures. As previously emphasized, continual, clear communication between the anesthesiologist and the surgeon is essential to coordinate ventilation and periods of brief apnea during suture placement.

A conservative point of airway is chosen and the trachea is divided. Further dissection of the airway can be done by elevating the transected ends of the airway, again staying very close to the trachea at all times. In order to facilitate mobilization of the trachea and reduce tension, a variety of maneuvers can be performed. The simplest measures to reduce tension are blunt dissection of

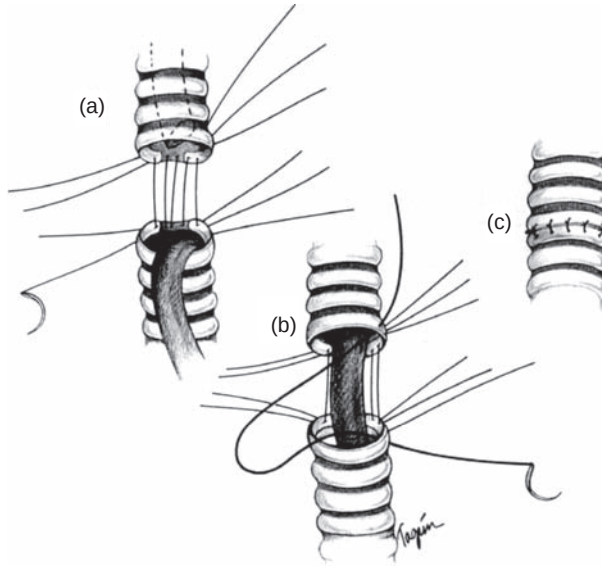

Figure 7.3 Tracheal resection and reconstruction. (a) Sterile ventilatory tubing placed in distal airway; (b) placement of interrupted absorbable sutures and replacement of endotracheal tube; (c) tracheal anastomosis.

the pretracheal plane and gentle flexion of the neck. This should be done on *all* patients. Intrapericardial pulmonary hilar release, similar to that described for bronchoplastic procedures, allows elevation of the distal trachea by approximately 2 cm, but is rarely required. Suprahyoid release may give an additional 1–2 cm of mobility to the airway if excessive tension exists, and this is the first maneuver that should be performed if necessary. Patients must be carefully assessed for aspiration following suprahyoid release. This risk usually resolves in 1–2 weeks, and there is less incidence of discoordinate swallowing than occurs with suprathyroid release, the latter maneuver being largely abandoned [24, 25].

If resection and reconstruction can be accomplished, the diseased segment is removed. Traction sutures (2–0 Vicryl) are placed in the proximal and distal ends of the trachea in the mid-lateral position (Figure 7.3a). They should be placed 3–4 mm from the cut ends and around a tracheal cartilage. Individual anastomotic sutures (4–0 Vicryl) are placed starting in the midline posteriorly (Figure 7.3a and b). The sutures are placed so the knots will be on the outside. Each suture is clipped to the drapes to maintain proper order. Once all of the sutures are placed, the neck is flexed and maintained by the anesthesiologist, the oral endotracheal tube is advanced across the anastomosis, and the traction sutures are tied. At this point, each anastomotic suture is then tied in the reverse order of placement to avoid entanglement of the sutures (Figure 7.3c).

The wound is then flooded with saline and the anastomosis is checked for any air leaks. This is done by deflating the balloon of the endotracheal tube, occluding the nose and mouth, and ventilating to a pressure of 30–40 mm Hg. Any air leaks should be repaired, even if it means doing the entire anastomosis over again. If the anastomosis lies directly under the innominate artery, it is preferable to cover the anastomosis with a pedicled strap muscle. The previously divided thyroid isthmus is reapproximated and the wound closed in layers. A small drain should be placed to evacuate the wound. To secure the patient's neck in a flexed position, a heavy suture is placed from the submental crease under the chin to the presternal skin. Patients are told before surgery to expect this. The chin stitch is divided on postoperative day 7.

Postoperatively, the patient should be extubated in the operating room. Flexible bronchoscopy is a useful tool to inspect the anastomosis and clear secretions in the OR during the immediate postoperative period and a low threshold for its use should be maintained during the hospital stay. Pulmonary toilet is paramount with aggressive chest physiotherapy and early ambulation. A diet is initiated slowly with strict aspiration precautions and monitored by trained staff members. Follow-up flexible bronchoscopy is performed usually on postoperative day 7 to inspect the anastomosis and the chin stitch is cut. Upon discharge, the patient is instructed to avoid active extension of the neck, driving, and heavy lifting for approximately 3 weeks.

Management of complications

The most immediate complication is an inadequate airway in the postoperative setting. If this is anticipated, a protecting tracheostomy should be considered. If one is to be placed, it should be at least two tracheal rings below the anastomosis. A pedicled strap muscle, based inferiorly, should be placed and secured over the anastomosis to separate it from the tracheostomy site and to serve as a barrier to contamination from secretions. Tracheostomy site care should be routinely practiced. If uncertainty exists, it is best to place the strap muscle over the anastomosis and mark the spot for the proposed tracheostomy with a suture to allow localization of the proper site if this becomes necessary. If airway compromise persists, the patient should be brought to the operating room, where a small (usually 5.5 mm diameter), uncuffed endotracheal tube should be placed in a controlled setting. This tube can be inserted by placing it over a flexible pediatric bronchoscope. It can be left in for 48 hours, at which time the patient should be returned to the operating room and extubated under a light general anesthetic. Persistent airway problems necessitate placement of a tracheostomy.

Airway problems that develop in the first 24–48 hours may be related to edema. Racemic epinephrine, 24 hours of steroids, and diuresis should be sufficient to manage and reduce the swelling. If this fails, the patient should be brought to the operating room, where a small (usually 5.5 mm diameter) uncuffed endotracheal tube should be placed in a controlled setting. This is best done with the aid of a flexible bronchoscope.

Wound infections have been relatively uncommon (<2%). Preoperative use of Peridex, mouthwash, and intraoperative irrigation with saline and dilute antibiotic solution should be routinely employed. Concern over infection is one reason to always try to cover the anastomosis with viable tissue (thyroid isthmus or strap muscle). A superficial wound infection should be managed with dressing changes and antibiotics. Bronchoscopy should be done to check the integrity of the anastomosis.

The presence of subcutaneous emphysema or an air leak through the wound drain usually means a small leak in the anastomosis. The patient should be returned to the operating room and the wound explored to inspect the anastomosis and the adjacent trachea. If the leak can be identified, it should be repaired with sutures and buttressed with a pedicled strap muscle.

The presence of subcutaneous emphysema and respiratory distress usually heralds more serious problems with the anastomosis. Dehiscence and separation is a life-threatening problem. Great judgment is required to determine how best to manage this problem. If the separation is only partial, a tracheostomy or T-tube should be placed through the separation. Complete separation is a very serious situation. If enough length of the distal airway exists, it can be secured to the skin as an end-stoma. Insufficient length of the distal airway requires creative solutions to secure the airway. A tracheostomy tube should be placed and buttressed with muscle flaps to wall it off from surrounding vascular structures. The proximal airway should be closed or covered with a muscle flap. A T-tube can be used if the distance of separation is not too great. Muscle flaps should be utilized to buttress the T-tube.

Late anastomotic stenosis is usually a result of exuberant granulations or stricture from ischemia or slow separation. Granulations are uncommon now that absorbable sutures are used. Mechanical debridement, lasering, or steroid injection may be utilized to manage the granulations with varying degrees of success. Early stricturing can be managed transiently with dilation. If dilation is unsuccessful, a tracheostomy or T-tube may be necessary. Whichever tube is chosen, it should be placed through the most damaged portion of the airway to insure as much viable trachea as possible for future reconstruction. If recurrent stenosis develops, reoperation is possible in highly selected patients. A period of at least 3 months should elapse before attempted resection and reconstruction.

Paralysis of one vocal cord or performance of a suprahyoid laryngeal release predisposes patients to aspiration. This is usually a temporary problem. Speech pathologists are helpful in instructing patients about swallowing techniques that minimize aspiration. If these maneuvers fail, a temporary gastrostomy tube may be required until the patient no longer aspirates. Prolonged symptomatic vocal cord paralysis or bilateral cord paralysis may be amenable to otolaryngological techniques to lateralize a vocal cord, improving glottic opening, or to move a vocal cord to the midline if aspiration persists.

Table 7.2 Results of primary reconstructions.

	Intubation no.	*%*	*Neoplasm no.*	*%*
Good	232[a]	83.2	77[b]	90
Satisfactory	27[c]	9.6	–	–
Failed/poor	11	4.0	1	1
Death	5	1.8	8	9
Lost to follow-up	4	1.4	–	–
Total	**279**		**86**	

[a] 7/232 required reoperation for stenosis.
[b] 6/77 required reoperation for stenosis.
[c] 2/27 required reoperation for stenosis.

One of the most dreaded postoperative complications is a tracheoinnominate artery fistula [26]. It is an uncommon problem (<0.8%). It is best avoided by avoiding direct dissection of the innominate artery itself and by interposing a pedicled strap muscle as described previously. If a tracheoinnominate artery fistula develops, the patient should immediately be taken to the operating room. An endotracheal tube, placed with the balloon inflated at the anastomosis, should temporarily control the hemorrhage. A sternotomy is done and proximal and distal control of the artery obtained. The artery is divided and the two ends oversewn. The management of the airway depends upon the nature of the injury. If the tracheal defect is small, repair and buttressing

Table 7.3 Complications following tracheal resection and reconstruction in 365 patients.

Complication	*Intubation*	*Neoplasms*	*Fault*
Granulations	28	10	Nonabsorbable sutures
Separation	4	6	Excessive tension, devascularization
Air leak only	–	1	–
Stenosis (tension)			Granulation, separation
Partial	6	3	
Complete	15	–	
Hemorrhage	2	1	Innominate: incorrect dissection, injury Pulmonary aa: no tissue interposition
Tracheo–esophageal fistula	1	–	–
Esophagocutaneous fistula	–	1	–
Cord dysfunction	5	3	Surgical injury
Aspiration	1	–	Neurological deficit preop., short trachea, laryngeal release
Wound infection	6	–	
Laryngeal edema	1	–	
Respiratory failure	–	2	
Pneumonia	–	2	
Persistent stoma	5	–	

Table 7.4 Effect of experience (postintubation lesions).

	Case no.	
	1–139	*140–279*
Deaths	4	1
Failures	13	7
Complications	42	30

with muscle or omentum may be possible. If there is circumferential injury to the anastomosis, placement of a tracheostomy through the damaged portion is preferable. We have tended to mobilize omentum passing it substernally to bury the divided ends of the innominate artery and reinforce the tracheal repair.

Results

Resection and reconstruction of the trachea for postintubation/post-traumatic stenoses and for neoplasms is successful in over 90% of patients [9], though the success rate for idiopathic stenosis is somewhat less [27]. An important caveat to those who plan to manage tracheal pathology is that the first time surgical procedure yields a markedly greater chance of success than reoperation. Accordingly, harbingers of success are proper patient selection, judicious timing of surgery, meticulous attention to technical details, and experience (Tables 7.2–7.4). However, complications may still arise. In such cases, proper recognition and management can still lead to a favorable outcome [28–30].

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CHAPTER 8

Complications of Lung Volume Reduction Surgery

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Introduction

As many as 2 million Americans have emphysema [1], a progressive disease that results in a continued decline in pulmonary function. When pulmonary function tests document a forced expiratory volume in 1 second (FEV_1) of less than 30% of the value predicted by nomograms, the 3-year mortality risk has been estimated at 40–50%. Medical therapy is the mainstay of treatment [2]. While lung transplantation is a viable option, the scarcity of available donors, and comorbidities of patients with advanced chronic obstructive pulmonary disease (COPD) make this a limited option open to a select few. The recent changes in the allocation of donor lungs have further diminished the impact of lung transplantation since lungs are now increasingly allocated to patients with pulmonary fibrosis and other rapidly progressing causes of pulmonary failure.

An additional surgical therapy, lung volume reduction surgery (LVRS) has matured to become a viable treatment modality in the last two decades. Apart from lung transplantation, LVRS is the only form of surgical therapy for emphysema, which has withstood rigorous investigation. In 1957, Dr. Otto C. Brantigan proposed a surgical treatment for patients disabled by diffuse pulmonary emphysema. Brantigan resected peripheral lung tissue, anticipating restoration of the elastic recoil of the lung and improved mechanics of the thorax and diaphragm. He performed the procedure with a unilateral thoracotomy and added a radical hilar denervation procedure with the belief that this would decrease pulmonary secretions. Overall improvement was reported in 75% of the patients. However, Brantigan provided few quantitative corroborating data, and the in-hospital mortality rate was 19%. As a result, Brantigan's procedure did not gain wide acceptance.

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Observations in lung transplant patients led Cooper to resurrect Brantigan's ideas in 1993 [3]. It was observed that the transplantation of normal lungs into patients with emphysema led to restoration of a normal thoracic configuration. Emphysema is unevenly distributed throughout the lungs resulting in regional variation in both structure and function. The success of LVRS depends on exploiting the heterogenous distribution of disease. Similar to Brantigan's procedure, approximately 30% of the patient's lung volume was removed by performing peripheral resection of the most emphysematous portions. He used linear cutting/stapling devices, buttressed the suture line, and performed a simultaneous bilateral procedure through a median sternotomy. The procedure was considered palliative and was designed to reduce dyspnea, increase exercise tolerance and performance in activities of daily living, and improve quality of life. In most patients, these goals were achieved with concomitant physiologic improvement in airflow limitation, hyperinflation, and alveolar gas exchange [3].

Enthusiasm for LVRS after this sentinel report led to its widespread application. However, analysis of data of patients enrolled in United States government sponsored health care (Medicare) revealed a 23% mortality at 12 months with this procedure [4]. Because of the high risks and costs associated with the application of the operation, Medicare funding for the procedure was stopped in 1996. The National Heart, Lung, and Blood Institute of the National Institutes of Health began a clinical trial to evaluate the benefit of the procedure [5]. The result of the effort, the National Emphysema Treatment Trial (NETT) began enrolling patients in 1999. In this review, we will discuss the lessons learned from the NETT and other studies regarding the avoidance of morbidity and mortality by rigorous patient selection, and careful postoperative care.

Avoiding complications by proper patient selection

The goals of the preoperative assessment are to identify patients who remain disabled by emphysema in spite of maximal medical therapy, to classify patients according to ability to benefit from surgery with an acceptable surgical risk, and to accurately identify and appropriately exclude those patients more likely to have a poor outcome.

The initial evaluation schema developed at Washington University has been refined by analysis of surgical results of the NETT trial and other studies (Table 8.1). As can be expected from our understanding of the pathophysiology of emphysema, this schema suggests that the patients who will have the best outcome from volume reduction surgery are those patients with marked hyperinflation, and heterogeneous involvement of emphysema. Ideally an isolated portion of the lung should be most affected, and be essentially nonfunctioning. The remaining lung, although emphysematous, should not be totally destroyed and must be capable of maintaining adequate gas exchange. The more closely a patient approaches this ideal model, the better the

Table 8.1 Discriminating selection criteria for lung reduction surgery.

	Suitable for LVRS	*Unsuitable for LVRS*
General	Disability despite maximal rehabilitation	Minimal disability after completing pulmonary rehabilitation
	Ability to meet rehabilitation goals	Inability to participate in rehabilitation
	Cessation of tobacco use >6 months	Continued use of tobacco significant comorbidity
	Weight 80–120% ideal body weight	Previous pleurodesis or thoracotomy
	Patient expectation of reasonable goals	Significant purulent secretions or predominant airways disease
		Inability to taper from high dose corticosteroid therapy
		Underweight, overweight
Anatomic radiographic evaluation	Marked emphysema	Minimal radiographically evident emphysema
	Heterogeneously distributed emphysema	Bronchiectasis
	• Large target zones of poorly perfused lung with marked parenchymal destruction	Homogeneously distributed emphysema
	• Large areas with better preserved lung	
	Marked thoracic hyperinflation	Minimal thoracic hyperinflation
		Chest wall or thoracic cage abnormalities
Physiologic evaluation	Marked airflow obstruction	Minimal to moderate airflow obstruction
	• FEV_1 <45% predicted	• FEV_1 >45% predicted
	• FEV_1 >15% if age >70 years	• FEV_1 <15% if age >70 years
	• FEV_1 or DLCO > 20% predicted	• FEV_1 or DLCO < 20% predicted
	Marked hyperinflation	Minimal hyperinflation
	• RV > 150% predicted	• RV < 150% predicted
	• LC > 100% predicted	• LC < 100% predicted
	Alveolar gas exchange	Disordered alveolar gas exchange
	• DLCO <80% predicted	DLCO <10% or >80%
	• $PACO_2$ < 60 mm Hg	$PaCO_2$ > 60 mm Hg
	• PaO_2 > 45 mm Hg	PaO_2 < 45
	• Exercise O_2 requirements < 6 lpm	Exercise O_2 requirements > 6 lpm

Table 8.1 (*Continued*)

Suitable for LVRS	*Unsuitable for LVRS*
Cardiovascular function	Cardiovascular dysfunction
• Normal ejection fraction	• Diminished ejection fraction
• No significant coronary artery disease	• Significant coronary artery disease
• No pulmonary hypertension	• Mean PAP >35 mm Hg
	• Or systolic PAP >45 mm Hg
Exercise	Exercise
• Postrehabilitation 6-minute walk distance > 500 ft	• Postrehabilitation 6-minute walk distance < 500 ft
• Able to complete 3 minutes of unloaded pedaling on a cycle ergometer	• Unable to complete 3 minutes of unloaded pedaling on a cycle ergometer

anticipated outcome. Some of the most salient points in the evaluation include the following favorable selection characteristics: (i) airway obstruction produced predominantly by emphysema rather than by intrinsic airways disease such as asthma or bronchitis, (ii) emphysematous lungs with sufficient regional variation in the distribution of emphysema (heterogeneity) to provide target areas of virtually nonfunctioning lung accessible to surgical resection, and (iii) marked hyperinflation of the thorax.

In addition to the very important history and physical examination, the evaluation relies heavily on physiologic and imaging studies. The specific methods for assessing patients for surgery are listed in Table 8.1. Inspiratory and expiratory chest radiographs are used to evaluate the degree of thoracic hyperinflation as evidenced by downward displacement and flattening of the diaphragm, as well as distention of the thorax with enlarged retrocardiac and retrosternal air spaces. The chest radiographs also provide an initial indication of the overall severity and relative distribution of emphysema. Other findings on these films, such as marked pulmonary scarring, pleural disease, infiltrates, adenopathy, effusions, and cardiovascular abnormalities, may be useful for identifying comorbidities that might be contraindications for surgery.

The standard chest computed tomography (CT) examination without intravenous contrast provides critical information for the selection process. Most importantly, it provides a detailed depiction of the severity and distribution of emphysema. This is most helpful in characterizing whether the patient's limitations are secondary to emphysema or airway disease. It is also important in establishing the presence and location of target areas. High-resolution CT provides increased sensitivity for revealing occult bronchiectasis or underlying interstitial lung disease. In addition, CT may demonstrate evidence of underlying pathology, such as pleural disease, infection, cancer, or cardiovascular disease, any of which might preclude LVRS.

Nuclear medicine ventilation–perfusion lung scans depicting regional blood flow pattern provide a valuable roadmap for surgery. The absolute severity of emphysema cannot be assessed because the distribution of the perfusion agent is relative, but the presence of diffuse or upper or lower lobe-predominant disease, and the degree of such heterogeneity, can be assessed.

There is considerable variation in the interpretation of CT scans to evaluate patients for LVRS. As the entire lung is affected to some degree by emphysema, it may be difficult to assess whether the disease is truly heterogeneous in distribution. Hersh and colleagues [6] assessed the ability of radiologists and pulmonologists to interpret the distribution and severity of emphysema on CT imaging and they demonstrated considerable interobserver variability. Quantitative measures based upon CT scan densitometry may improve discrimination between heterogenous and homogenous disease. In the NETT trial, a single radiologist evaluated a given patient's CT scan. Illustrating the difficulty of radiographic interpretation using visual scoring methods, the authors reported that 63% of patients were classified as having "upper lobe predominance," but 54% of the same group of patients were classified as having "heterogenous" involvement [7]. The fact that the proportion described as upper lobe predominant is higher than the fraction described as heterogenous points out the subjectivity inherent in these assessments.

Assessment of cardiac function is a critical portion of the evaluation for LVRS. This includes an appraisal for underlying pulmonary hypertension, coronary artery disease, and other significant cardiac dysfunction. Rest and exercise dobutamine echocardiography, radionuclide ventriculograms, thallium imaging, and other similar studies provide useful information for risk stratification. However, these noninvasive tests of cardiac function are often limited. Exercise testing is often not useful owing to the patient's inability to exercise to heart rate limits. Transthoracic echocardiography may not provide adequate information because of chest hyperinflation, resulting in poor visualization of the heart. Concern for inducing bronchoconstriction may limit the use of dipyridamole or adenosine. As a result of these limitations, to obtain a definitive answer, many LVRS candidates eventually undergo right and left heart catheterization.

Review of the surgical results of LVRS reveals several predictors of surgical mortality. Most notably, the NETT trial initially enrolled and randomized patients who did not meet the concepts that form the basis of the surgery—that is, those who lacked appropriate targets to resect, or those with severe impairment of the remaining lung. Patients with FEV_1 <20% of predicted values *and* homogenous distribution of emphysema on CT scan, *or* those with FEV_1 <20% of predicted values *and* carbon monoxide diffusion capacity (DLCO) of <20% predicted were declared "high risk" by an early outcomes paper from the NETT. These patients had no change in ability to exercise, no improvement in FEV_1, no change in 6-minute walk test, no improvement in quality of life, and had a 16% 30-day mortality rate [8]. The high mortality rate seen in these high-risk patients prompted a modification of the NETT protocol to exclude

from randomization any patients meeting these criteria. However, these criteria may not present an absolute contraindication. In a retrospective review of patients meeting the NETT "high-risk" criteria for FEV_1 and DLCO, our group did not demonstrate excess mortality, and did show improvement in respiratory function in patients with high-risk characteristics in the setting of heterogeneity and target areas [9]. This suggests that the presence of suitable anatomic heterogeneity may be the most important determinate of outcome. In the follow-up publication on the morbidity and mortality experienced by patients undergoing LVRS, the NETT trial investigators reported a 5.5% 90-day mortality among the 511 nonhigh-risk patients who were randomized to surgery and underwent LVRS. Nonupper lobe-predominant emphysema was the only predictor of 90 day mortality [10].

In summary, (i) patients with emphysema may be effectively distinguished from those limited by intrinsic airway disease by history, physical examination, and, most useful, pulmonary CT; (ii) the degree of regional parenchymal destruction is analyzed by CT of the chest, and the regional distribution of function is assessed by radionuclide ventilation–perfusion lung scanning; and (iii) thoracic distention is evaluated by chest radiograph and plethysmographic determination of lung volumes. All patients will benefit to some degree from pulmonary rehabilitation, but only a selective few are candidates for LVRS because of significant comorbidities, homogenous distribution of disease, or inadequate pulmonary reserve. There is an element of subjectivity to section criteria that is difficult to capture in a book chapter and springs from experience. The authors of this chapter continue to be conservative in patient selection. Eligibility criteria are summarized in Table 8.1.

At Washington University Medical Center, historical data from the LVRS heyday of the 1990s recall that approximately 80% of patients referred for this procedure have been excluded from surgery, most commonly because of lack of target areas for surgical resection (30%), insufficient thoracic distention (16%), and the presence of significant comorbidities (16%) [11]. Of note, 8% of referrals were denied surgery because their forced expiratory volume in 1 second (FEV_1) was too well preserved, that is, they were too good to justify the risk of surgery. In the NETT experience, a similar selection process was observed: of 3777 patients considered for entry into the NETT trial, only 1218 were randomized [7].

Preoperative medical management

Foremost among medical interventions, the cessation of smoking is essential. Most programs require at least 6 months of abstinence from tobacco prior to considering patients for surgery. In addition, all patients should be enrolled in a structured pulmonary program. The comprehensive program should include exercise training, optimization of medical management, patient education, psychosocial assessment, and optimization of nutrition.

A graded exercise program is essential to pulmonary rehabilitation. Many patients with COPD remain breathless and fear overexertion. As a result, these patients become increasingly sedentary, leading to progressive deconditioning. Patients then experience a diminished exercise tolerance, and a self-replicating cycle continues. A graded exercise program should be initiated immediately for all patients. Exercise acts as a cornerstone of the patients' return to a more active lifestyle.

Exercise training is designed to decrease exertional dyspnea and to increase endurance and maximal exercise capacity. Prior to surgery, patients in the Washington University Medical Center program are required to complete an exercise program that has a minimum goal of 30 minutes of daily continuous exercise (at least 5 days per week) on a treadmill or stationary bicycle. Heart rate targets are set at 80% of the maximum predicted heart rate. Patients are periodically re-evaluated throughout the graded exercise program with 6-minute walk tests. A program used in the NETT trail is described by Ries *et al*. [12]. The Joint Commission on Accreditation of Hospitals and Organizations (JCAHO) uses a minimum performance of 3 minutes of unloaded pedaling on a stationary bicycle as a condition for acceptance for LVRS surgery.

Oxygen therapy for the hypoxemic patient is the only medical therapeutic intervention that has been shown to increase survival for COPD, as demonstrated in randomized controlled trials [13]. In addition, exercise-induced hypoxemia is common in patients with severe COPD, and oxygen supplementation may improve exercise performance. Oxygen therapy is indicated for any patient with a $PaO_2 < 55$ mm Hg, or oxygen saturation $<88\%$. If a patient has evidence of cor pulmonale or a hematocrit of $>55\%$, oxygen therapy is indicated even with higher baseline PaO_2 levels. Patients should be evaluated during exercise as well as at rest.

Bronchodilator therapy is useful in symptomatic airflow limitation. Although a large proportion of patients with COPD may have partially reversible airways disease aerosolized bronchodilators have not been demonstrated to slow the rate of deterioration of lung function. A stepwise approach to employing adrenergic receptor agonists, anticholinergics, and possibly methylxanthines is routinely recommended in COPD; however, the patients evaluated for surgery have markedly compromised pulmonary function, have often already progressed along the stepwise approach, and now require intensified "maximal" therapy [2]. Virtually all patients have previously been prescribed metered-dose inhalers, yet many patients use them incorrectly. Thus, it is imperative to observe inhaler use and then instruct patients on how to correctly use the inhaler, possibly with the addition of a spacer.

As many as half of the patients evaluated for LVRS at our medical center are on long-term systemic corticosteroid therapy. Unfortunately, most patients with stable COPD do not show improved airflow with oral steroid therapy. There are no prospective data demonstrating preserved respiratory function with the use of systemic steroids. The subset of COPD patients with a large

component of reactive airways disease may benefit from steroid therapy, but studies have not definitively supported this suggestion. Therefore, reduction or elimination of systemic corticosteroids should be the goal of a comprehensive rehabilitation program. Similarly, the role of inhaled steroid therapy is undefined. Inhaled steroids may diminish the number of exacerbations requiring hospitalization. The benefit to patient mortality and decline in pulmonary function is unknown.

For those patients who are dependent on oral steroids preoperatively, tapering to the lowest possible dose during the rehabilitation phase is mandatory to avoid the associated increased postoperative risks, including poor wound healing and perioperative infection. For those patients who remain on long-term systemic corticosteroid therapy within weeks preceding surgery, supplementation with "stress dose" hydrocortisone is required. Switching the patient from oral steroids to inhaled steroids may not eliminate the risks of impaired wound healing. In fact, preoperative use of inhaled steroids, but not oral steroid use, was an independent risk factor for increased duration of air leak in the NETT trial [14]. The authors speculated that this may have been due to an increased concentration of steroids in the lung.

Education, an important component of pulmonary rehabilitation, may include teaching patients about the basic physiology of COPD, medical management options, and the importance of compliance. This teaching may result in improved understanding and coping, decreased anxiety, and positive behavioral changes. As part of the initial comprehensive rehabilitation evaluation, counseling may be offered to address coping with anger, depression, and fear related to the chronic illness. In addition, counseling provides encouragement and support. Patients may also benefit from enrollment in a support group.

Malnutrition, especially that marked by progressive weight loss and muscle wasting, commonly occurs in patients with marked COPD and is associated with increased mortality. Patients may benefit from nutritional counseling and the use of nutritional supplements when indicated.

Although a structured pulmonary rehabilitation program may not significantly improve pulmonary function tests, many authors have documented an improvement in exercise tolerance, dyspnea, and quality of life with this nonoperative intervention. After successful completion of the preoperative program, the average increase in the distance walked in 6 minutes has been 20% [11, 15]. During the preoperative program, patients also experience decreases in dyspnea. The NETT investigators reported similar improvements in ability to exercise, in 6-minute walk test, sensation of dyspnea, and quality of life [12]. In the NETT trial, 16% of patients were reassessed to be in the "high exercise" functioning group, although they were initially assessed to be of "low exercise" function. More importantly, 5% of patients were found to have deteriorated during the course of pulmonary rehabilitation. This decline during evaluation and treatment is of considerable prognostic benefit and should be viewed with caution.

Operative approach

A number of variations to the surgical approach have been described. Both thoracoscopic (VATS) and median sternotomy (MS) have been widely utilized at different centers. In the randomized NETT trial, of the surgical procedures performed, 359 underwent MS and 152 patients underwent bilateral VATS procedures [4]. If a center had expertise in both approaches, the patients in the surgical arm were randomized to either approach (29% of patients, $n = 148$). The authors reported no intraoperative death with both approaches and equal 30-day mortality. There was no difference in complication rate, including the incidence of sustained air leak. The median hospital length of stay was 1 day longer for the MS group, and the costs associated with the operation were less in the VATS group, likely driven by the shorter length of stay. The only reportable difference between the two surgical approaches was that the VATS group achieved independent living (discharge to home) sooner that the MS group. By 1 year, the functional outcomes were identical.

We have favored a MS approach due to comfort and experience with the strategy. More recently, the JCAHO certification of LVRS Centers of Excellence specifies that the operation must be done in the manner with which experience can be demonstrated. Preoperatively, a thoracic epidural catheter is placed under fluoroscopic guidance to ensure optimum postoperative relief of pain with minimal need for systemic narcotics or respiratory depressants. A left-sided double-lumen tube is used to provide isolated ventilation to either lung. The operative approach we have employed was described by Cooper and Patterson [16].

Before sternal division, a long, curved sponge forceps holding a rolled gauze is inserted upward behind the sternum from the subxiphoid position and is used to sweep the mediastinal pleura on either side away from the midline. This avoids entry to either pleural space at the time of sternal division. The intact pleura can be deliberately incised following sternotomy, which keeps the opposite lung from protruding into the operative field when reduction of the first lung is taking place. Disconnection of the endotracheal tube for a minute or two before sternal division will also reduce the chances of pleural or pulmonary injury by the sternal saw.

The initial lung is deflated, and any adhesions are carefully dissected free to avoid laceration of the surface of the lung. Great care should be taken here, as a small injury to lung meant to be preserved will result in large and possibly prolonged air leaks. Most emphysema patients have few or minimal adhesions, although occasionally, widespread dense adhesions are encountered, usually as a result of a previous pneumonia. Once the lung has become atelectatic, direct visualization of most areas is quite satisfactory. After 5–10 minutes of deflation, the less-diseased portions of the lung deflate by the process of absorption atelectasis. However, the more destroyed portions of the lung, those generally targeted for resection, remain distended owing to the loss of elasticity and the absence of blood flow. Simple cautery puncture of the surface of the region to be excised usually leads to immediate deflation

because of the enormous collateral ventilation from one portion of the lung to another in patients with severe emphysema.

Most candidates for bilateral lung volume reduction have a pattern of upper lobe-predominant disease. About 80% of the right upper lobe is excised by multiple applications of a linear stapler device buttressed with strips of reinforcing material attached to the surfaces of the stapler before its application. There are many such products that are commonly available. The right inferior pulmonary ligament is occasionally divided to improve the ability of the remaining lung to fill the apical pleural space. On the left side, the lingula is generally spared, as it is usually less diseased than the superior subdivision. Thus, about 60% of the left upper lobe is excised with multiple applications of the linear stapler.

If there is concern that the remaining lung will not easily reoccupy most of the upper portion of the pleural space, then the apical pleura can be released from the chest wall to form a so-called pleural tent, which loosely drapes over the upper surface of the remaining lung. The space above the tent fills with fluid, resulting in a temporary "soft thoracoplasty." It is important to remember that the purpose of LVRS is not to excise all grossly diseased lung, but to achieve sufficient volume reduction to improve respiratory mechanics and the function of the remaining lung. An overly aggressive approach may increase postoperative morbidity and mortality, whereas insufficient reduction will diminish the magnitude and duration of benefit achieved. The exact amount of lung to be resected is an elusive and subjective issue.

While some authors have suggested that a unilateral approach may be preferred due to the benefits achieved with unilateral LVRS, and with the implication that unilateral LVRS is intrinsically less morbid, larger studies have demonstrated this to not be the case. In a sequential case series of 166 patients utilizing VATS technique, McKenna and coworkers demonstrated that patients undergoing unilateral LVRS had good response to improvement in FEV_1 (31% change from baseline) and oxygen independence (35%), but a bilateral operation yielded an even greater improvement in FEV_1 (57% change from baseline) and greater oxygen independence (68%) [17]. However, operative morbidity and mortality were the same in both groups. Given the improvement with unilateral surgery, unilateral operation may still be offered in some patients not candidates for a bilateral operation due to prior unilateral thoracic intervention or inappropriate anatomy for bilateral LVRS [17]. The NETT did not address the issue of unilateral procedures and, therefore, the Medicare coverage decision in the USA does not address unilateral LVRS procedures.

Postoperative care and avoidance of specific complications

Virtually all patients are extubated in the operating room. Patients rarely require reintubation in the initial 48 hours. However, significant hypercarbia and acidosis may be present for several hours owing to the residual effects of the anesthesia or incomplete analgesia. Proper anesthetic technique, and a

functioning epidural for pain management are essential to successful extubation.

Air leak

The most frequent complication of lung resection in the patient with emphysema is air leak. The chest tubes in these patients are attached to water-seal drainage without the use of suction unless there is a significant symptomatic pneumothorax or worsening subcutaneous emphysema. In the event suction is required, as little suction as possible is applied initially(10-cm water). Our practice reinforces the work of Cerfolio and colleagues on the management of air leaks [18–21]. The loss of elastic recoil and the obstructive physiology of the remaining emphysematous lung make it resistant to the usual loss of volume ordinarily associated with a postoperative pneumothorax. The fragile nature of the lungs renders them more susceptible to the adverse effects of increased transpulmonary pressure and overdistention caused by chest tube suction. The use of suction has a tendency to increase the magnitude and prolong the duration of air leaks in these patients.

The management of air leaks requires patience. In our early experience with LVRS, 3% of patients underwent reoperation for sustained air leaks. Currently, we rarely use this strategy. We have discharged a number of patients with a chest tube and Heimlich valve in place, as long as the lung remains expanded off suction and the patient and family feel comfortable with such a plan.

We have avoided the use of pleurodesis as the inflammatory reaction of doxycycline or talc may exacerbate the tenuous respiratory status of these patients. Besides the pain caused by the procedure, the detrimental effects or pleurodesis are worse in patients who smoke. Tschopp and colleagues demonstrated a 25% reduction in TLC 10 days after talc pleurodesis, and a reduction in FEV_1 has been demonstrated in smokers undergoing talc pleurodesis in long-term follow-up [22, 23]. Similarly, Rice and colleagues were unable to demonstrate a reduction in air leak duration with the use of doxycycline pleurodesis [24]. Because bedside pleurodesis is an often painful experience for the patient, the lack of proven benefit should make it increasingly uncommon in the absence of any new reports that endorse its use.

The best method to manage air leaks is intraoperative prevention. The method of lung parenchyma transection using buttressed staple line (bovine pericardium or other substance) has also been extensively studied. In Cooper's series of 250 patients undergoing LVRS, 45.2% of patients suffered parenchymal air leaks lasting greater than 1 week [11]. All patients underwent bovine pericardial strip reinforcement of the staple line. In the NETT trail, 90% experienced an air leak in the first 30 days [14]. The median duration was 7 days. Within the NETT trail, the occurrence was independent of the type of incision (MS vs. VATS), and of the use or nonuse of a staple line buttressing material. However, despite the NETT report that fails to support the practice of buttressing, most patients received some form of staple line reinforcement. One smaller randomized study of patients undergoing VATS

for bilateral LVRS demonstrated 39% incidence of air leak in the bovine pericardium group, and 77% incidence in the control group [25]. There was also a decrease in the duration of air leak with the use of staple line reinforcement. The authors of that study were unable to demonstrate a change in the length of hospital stay attributable to the diminished duration of air leak complications. We continue to advocate the routine use of staple line buttressing material despite the mixed evidence surrounding its use.

In our experience, the use of biological sealants has not been useful in the prevention of air leaks. Supporting our practice, a metaanalysis published by the *Cochrane Database of Systematic Reviews* of 12 trials enrolling 1146 patients utilizing biological sealants demonstrated no difference in the duration of an air leak in 6 of the randomized studies [26]. Only one trial demonstrated decrease in length of chest tube duration or hospital stay with the use of a biological sealant. A report currently in press (Lardinois, JTCVS 2008) did demonstrate a benefit in the use of an autologously derived fibrin sealant in the setting of LVRS performed without staple line buttresses. More investigation is needed in this area to understand the exact role for sealants.

Pulmonary secretions

In addition to adequate pain relief, early ambulation, and vigorous chest physiotherapy, postoperative management is directed at management of secretions. Our practice has been to place a mini-tracheostomy or small caliber tracheostomy device in patients who require frequent suctioning postoperatively. Maintaining a low threshold to perform flexible bronchoscopy is essential. The sudden disappearance of a previously large air leak may indicate lobar plugging and should prompt expeditious bronchoscopy to investigate and clear the blockage. Again, we stress the importance of recognizing patients who produce excessive sputum prior to the operation, as we feel that it is a relative contraindication to surgery and have cancelled an operation when the preoperative bronchoscopy has demonstrated copious and purulent secretions. Sputum is routinely submitted for bacteriologic analysis and we have little hesitation to broaden antibiotic coverage empirically.

Gastrointestinal complications

Gastrointestinal complications have been observed in emphysema patients undergoing LVRS [27]. While the link between emphysema and GI complications is uncertain, many of the early LVRS reports included an unexpectedly high rate of major complications due to bowel ischemia, perforation, or ileus (9.4%) and a very high rate of less severe complications such as nausea or vomiting (23%) [28]. Diabetes, steroid use, and multiple medications for pain control have been associated with major GI complications. Vigilance is necessary to identify and respond to these complications early as even as "minor" complication of nausea and vomiting may lead to aspiration and significant pulmonary compromise. We are aggressive in the use of nasogastric tube decompression if gastric distension is identified, or if the patient is having bouts

of emesis. All patients are placed on a bowel regimen to prevent or relieve constipation. We have a low threshold to obtain CT imaging of the abdomen for persistent abdominal complaints, or to utilize colonoscopy to relieve colonic distension.

Cardiovascular complications

Major cardiac morbidity including arrhythmia, myocardial infarction, or pulmonary embolism occurred in one-fifth of emphysema patients undergoing LVRS [10]. Advanced age and advanced lung disease are the predictors for both major pulmonary and cardiovascular morbidities. Our strategy has been to identify these patients preoperatively, and exclude the very high-risk patient population. As discussed in the prior section, many patients with severe emphysema require cardiac catheterization for preoperative cardiac risk stratification due to the limitations of less invasive testing.

Anxiety and delirium

A frequent cause of complications in all surgical patients, especially those undergoing surgery in the setting of emphysema, is postoperative delirium. Mortality is increased in patients with delirium [29]. Yildizeli and colleagues in a retrospective study of patients undergoing thoracic surgery identified advanced age, sleep deprivation, diabetes management and electrolyte abnormalities as key predictors of delirium in this patient population [30]. Prevention of this complication in the emphysema patient relies on minimizing stresses in the postoperative environment, treating any exacerbations in chronic diseases, and careful review of prescribed medications. Specifically, we have taken measures to ensure proper sleep hygiene by minimizing noise and other stimulation at night in our thoracic unit. We advocate the judicious use of narcotics, and try to minimize intravenous administration of narcotics in favor of an oral route as this has been demonstrated to decrease the incidence of postoperative delirium [31]. We minimize polypharmacy and strive to eliminate medications such as anticholinergics and antihistamines that have significant side effects in the elderly. Once delirium has manifested, it is important to evaluate for any medical condition which may have precipitated the crisis—for example, hypoxia, sepsis from pneumonia, alcohol withdrawal. After reversible causes are excluded, pharamacologic intervention with haloperidol (first-line agent) or benzodiazepene (second-line agent) is useful when the patient becomes a risk to themselves or others or hinders their treatment [29].

One cannot discount the contribution of anxiety induced by dyspnea (and vice versa) in the emphysema patient. While preoperative pulmonary rehabilitation and behavioral support can mitigate the symptoms, it is a frequent complaint in the postoperative period. Dyspnea accompanied by hypoxia requires urgent intervention and investigation for an underlying cause. Treating dyspnea-associated-anxiety may be more challenging. Nonpharmacologic interventions include changing the patient's environment to be less confining,

or improving ambient ventilation with portable fans. Oxygen administration, even in nonhypoxic patients has a significant beneficial anxiolytic role. We have even observed emphysema lung transplant recipients who preferred to wear nasal cannula even beyond the point that supplementary oxygen was needed. They simply felt reassured by the presence of the nasal prongs that had become part of their lives for many month or years before surgery. The most potent pharmacologic intervention remains the use of oral or intravenous narcotics [32]. While the mechanism is not entirely understood, conservative use of these drugs is effective, and avoids the unwanted side effects of respiratory depression. Anxiolytics such as benzodiazepines are often prescribed but have not been demonstrated to be efficacious in placebo-controlled studies of patients with COPD and dyspnea-related anxiety.

Results

LVRS was developed as a palliative procedure. In the highly selected patients presented in Cooper's series, Kaplan–Meier analysis demonstrated 67.7% survival at 5 years [11]. The more broad inclusion criteria of the NETT trial resulted in an interim report demonstrating increased mortality in LVRS patients with FEV_1 <20% and either a DLCO <20% or homogenous distribution of disease or both [8]. Excluding these admittedly high-risk patients, an overall survival advantage has been demonstrated in patients treated with LVRS as compared to best medical care. The survival benefit is greatest in patients with upper lobe-predominant disease and low baseline exercise tolerance (below the gender-specific 40th percentile for exercise capacity). This subgroup of patients also has the best improvement in exercise tolerance, and the most sustained benefit in self-assessed quality of life [33].

In the entire cohort of patients, exercise capacity improved (>10 watts work from baseline) in 23%, 15%, and 9% after LVRS at 1, 2, and 3 years, compared to 5%, 3%, and 1% of medically managed patients. Patients with upper lobe emphysema and high exercise tolerance demonstrated no survival benefit from surgery. These patients did, however, have improvement in exercise tolerance and quality of life, although the effects were less pronounced than in patients with upper lobe emphysema with low exercise tolerance. Overall there was wide variation in exercise capacity and quality of life perception in both surgical and medical groups making it difficult to predict long-term benefit for a given patient [33].

The physiologic changes responsible for the subjective and functional improvement experienced by patients remain unclear. Not all objective parameters improve to the same degree. For example, in any individual patient, a minor improvement in FEV_1 may be associated with a marked reduction in residual volume or with a very significant increase in PaO_2. However, the significant improvement observed in virtually all objective parameters for LVRS

patients as a whole confirms that the subjective benefits perceived by patients are related to physiologic alterations produced by the procedure.

In summary, LVRS is a viable option in only a select group of patients with emphysema. Patients must be motivated to participate in their own care and be willing to face real risks of morbidity and mortality to achieve the benefits of the procedure. They must have successfully completed pulmonary rehabilitation and continue to have significant dyspnea and they must have the appropriate anatomy to benefit from LVRS. Meticulous patient selection remains essential to minimizing morbidity and ensuring maximal benefit—improvement in physical function, mental well-being, and overall survival. Avoiding complications is paramount given the palliative nature of the procedure and the lack of reserve in these frail and compromised patients.

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CHAPTER 9

Complications of Lung Transplantation

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Complications of thoracic surgery

Lung transplantation

This chapter will discuss the complications directly related to lung transplantation. The procedure may be performed through several standard thoracic incisions. Wound complications related to these are discussed elsewhere in this volume. For purposes of discussion, the complications will be divided into those that occur early or late in the postoperative period.

Single lung transplantation is performed for patients with restrictive lung disease (e.g., pulmonary fibrosis), obstructive lung disease (e.g., emphysema), and pulmonary vascular disease such as primary pulmonary hypertension or in patients with pulmonary vascular disease secondary to congenital heart abnormalities [1]. It is generally performed through a standard posterolateral thoracotomy, although a median sternotomy has been used. Double lung transplant is generally performed for patients with septic lung disease such as cystic fibrosis or bronchiectasis of other etiologies. It is also sometimes done for pulmonary vascular disease or emphysema. The double sequential transplant procedure is usually carried out through a bilateral, anterior fourth interspace thoracotomy, either transversely dividing the sternum or leaving it intact [2]. Depending on the diagnosis, a patient may expect a 1-year actuarial survival in the 75% range as reported by the International Society of Heart and Lung Transplantation Registry [3].

Early complications

Early complications are related to the anastomoses, to the graft, or to recipient problems. The standard implantation procedure involves a bronchial anastomosis, and the two vascular connections of the pulmonary artery and left atrium. The left atrial anastomosis includes both the inferior and superior pulmonary veins. No reconstitution of the bronchial circulation is performed and

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consequently the implanted lung relies on the pulmonary circulation for both gas exchange and viability.

Air embolism

Most single lung transplants are performed without cardiopulmonary bypass. Once the anastomoses are completed satisfactorily, the graft is reperfused and ventilated simultaneously. The pulmonary circulation of the transplanted lung contains residual preservation perfusate and air, both of which must be prevented from entering the left atrium and, subsequently, the systemic circulation. This is accomplished by several maneuvers. The patient is placed in the extreme Trendelenburg position, so any inadvertent air in the left heart will not gain access to the cerebral circulation. With both the vascular anastomoses open, the atrial clamp is released, with the pulmonary artery (PA) clamp in place. This allows back bleeding through the lung and egress of unwanted material through the PA anastomosis. At this point, the PA anastomosis is completed and the atrial clamp reapplied. The PA clamp is partially removed to allow anterograde flow, and venting through the still open atrial anastomosis. Care must be taken to avoid full PA flow without the open anastomosis. Once a suitable period has elapsed, the atrial anastomosis is tied and the clamps are removed simultaneously, and the lung reventilated. The anastomoses are examined for good flow, and hemostasis. The bronchial anastomosis is inspected for air leak, which if present is corrected with additional sutures where necessary.

Reperfusion response

Most recipients will exhibit some degree of reperfusion response in the first 24–48 hours after the transplant procedure. This may vary from being almost imperceptible to a fulminant reaction with serious and occasionally lethal results. The precise etiology of the process is unknown but its pathophysiology suggests a pulmonary capillary leak syndrome. It does not seem to be related to ischemic time, preservation technique, or the precise method of reimplantation. Studies have failed to determine immunological phenomena as a basis. In the most common scenario, the patient will exhibit a modest but manageable decline in oxygenation, a fluffy infiltrate of a varying degree on a chest x-ray with pleural effusion or some amount of increased chest tube fluid output. The problem is self-limiting and managed by judicious fluid balance, diuresis, ventilation with positive end-expiratory pressure (PEEP), nitric oxide, and continued appropriate hemodynamic support [4]. The prophylactic use of inhaled nitric oxide appears to be a useful approach [5, 6]. Vascular anastomosis abnormality, particularly a partial venous obstruction, should be searched for and ruled out.

In the fulminant situation the situation can be more serious. The chest x-ray will demonstrate severe infiltrate or in some cases a complete ''white-out.'' Oxygenation may be difficult to maintain and hemodynamic instability is present. In extreme cases, extracorporeal membrane oxygenator (ECMO)

may be required to support the patient while the process runs its course [7, 8]. The inflammatory response clearly produces vasoactive substances because hypotension, depressed myocardial function, and peripheral profound vasodilatation can be observed. The patient may appear as if they are in septic shock. Many of these manifestations of ''primary nonfunction'' can be mimicked by a problem with the vascular supply to the graft, bacterial infection, and rejection, all of which must be eliminated as a cause of this picture. Most centers performing lung transplantation will have ECMO available if oxygenation and gas exchange become impossible in the severe case. Prolonged use of ECMO has resulted in poor results and high mortality but as a temporary strategy it has merit [9].

Various techniques have been suggested for use prophylactically in attempts to prevent the development of reperfusion response. However, none has been predictably effective in its prevention [10–12].

Vascular anastomotic complications

If care is not taken with the configuration and positioning of the vascular connections, poor flow and occasionally thrombosis can occur. This is a disastrous complication that must be recognized promptly and treated with a return to the operating room and correction of the problem. Several methods are available for the evaluation of these complications. A simple bedside bronchoscopy may reveal a severely ischemic airway, suggesting a problem with its blood supply. Conversely, if the airway is obviously well vascularized it is unlikely that the PA has completely thrombosed. A portable quantitative perfusion scan can also be performed in the ICU setting. In general, it should demonstrate preferential perfusion of the graft. If not, then usually rapid evaluation and re-exploration are necessary. Transesophageal echocardiography with an experienced operator can demonstrate pulmonary arterial flow, on the transplanted side. The venous flow may be more difficult to demonstrate, but obviously if there is good PA flow then venous outflow is satisfactory. Delay of intervention to perform angiography is seldom appropriate at this stage since prompt correction of a suspected problem is necessary to prevent irreversible damage to the graft. To emphasize, if there is sufficient concern about the vascular anastomoses being patent then a prompt re-exploration is indicated. Problems with the anastomoses discovered at thoracotomy are usually due to redundant vessel or impingement with local tissue such as pericardium. The anastomosis is revised and thombectomy performed.

Poor flow or lack of flow through the venous outflow tract can be a subtle diagnostic challenge. In the fulminant, thrombosed situation the patient will present with a pulmonary edema picture in the transplant and an abnormal transesophageal echocardiography (TEE). Technical misadventure with the anastomosis is usually the cause.

In most cases, where there is a complication with the anastomoses the diagnosis is readily apparent. However, on occasion because of the physiology and the residual native lung providing some support, it may not be

obvious. I have personally seen a transplant patient, with emphysema, extubated and breathing spontaneously, albeit with high oxygen requirements, with complete thrombosis of the PA anastomosis following single lung transplant. For this reason, it is mandatory to examine the vascular supply of the graft as a routine in the immediate transplant period using the tools described [13–15].

Bronchial anastomotic complications

Complications with the bronchus do not usually occur in the first few days post transplant. Before the patient is transferred from the operating room, the anastomosis is examined both at thoracotomy and bronchoscopically to ensure a satisfactory situation. Any problem should be diagnosed and corrected at that time. Later, problems with healing, usually on an ischemic basis, do not develop until necrosis of a portion of the donor bronchus occurs. This is frequently at the 10–14-day postoperative interval. Complete failure is decidedly uncommon and usually speaks of many other complications and an unsalvageable situation. The more common scenario will be the development of new mediastinal air or of a pneumothorax. A pneumothorax should be treated with the insertion of a chest tube. It does not always imply a bronchial anastomotic problem. In any case, a bedside fiberoptic bronchoscopy should be performed to examine and assess the status. A chest computed tomography (CT) scan is a very useful tool to determine the nature of the bronchus and the degree of contamination. Appropriate drainage, often done percutaneously under CT-guided control is necessary. With this and judicious antibiotics and pulmonary toilet the defect will heal satisfactorily. Sometimes such an occurrence in the early postoperative period will lead to subsequent stenosis or bronchomalacia.

Acute rejection

Acute rejection in the early post-transplant period is a very common occurrence. Standard immunosuppression is based on cyclosporine or FK506 in combination with steroids and usually with the addition of mycophenilate mofetil or imuran. Cytolytic therapy with antilymphocyte globulin (ALG), antithymocyte globulin (ATG), or monoclonal antibodies is infrequently required. Acute rejection usually presents at about day 5–7 but can occur at any time. The patient will demonstrate deterioration in oxygenation, sometimes flu-like symptoms, a low-grade temperature and nonspecific chest x-ray changes. These include a slight perihilar infiltrate or ''flare,'' a diffuse ground glass appearance or a small pleural effusion. There can also be no x-ray changes at all in the early stages. A moderate leukocytosis may also be observed. Infectious causes of this constellation of signs and symptoms are rapidly ruled out and the diagnosis of acute rejection made. Frequently, a diagnostic and therapeutic dose of ''pulse'' steroids will be given. If the problem is rejection, all of the abnormalities should subside within 8–12 hours if the process is in its incipient stages. A more established process will take longer

to reverse. Transbronchial biopsy at this point is appropriate but interpretation requires an experienced pathologist because of the changes associated with the inflammatory response to the ischemic period and reimplantation phenomena. Failure of the clinical diagnosis to respond promptly should trigger an immediate re-evaluation with transbronchial biopsies and if necessary, open lung biopsy to establish the diagnosis.

Late complications

The complications that occur later are usually related to infection, rejection, and airway problems.

Infection

Because the graft always and forever remains exposed to the environment it is susceptible to opportunistic infection. These may be viral, fungal, or bacterial.

Cytomegalovirus infection

Pneumonitis and generalized cytomegalovirus (CMV) disease are an ongoing problem in the long-term management of transplant patients. For logistic and practical considerations, very few programs perform donor to recipient matching with respect to CMV status. Donor CMV status at the time of organ retrieval is frequently unreliable. For this reason, many programs, including ours, have used an aggressive prophylaxis program against CMV. This involves high-dose ganciclovir, intravenously for the first 3 months post transplant when the level of immunosuppression is highest. CMV pneumonitis can mimic acute rejection, although it is often associated with a leukopenia. The diagnosis is made with transbronchial biopsy demonstrating the characteristic histological appearance and with the appropriate profile on serological testing. Treatment is with high-dose ganciclovir. Oral ganciclovir is available but is extremely poorly absorbed. Its efficacy is such that if the diagnosis is firm, intravenous therapy is required. Other viral infections seen include herpes and Epstein–Barr virus.

Bacterial infection is common and should prompt a rapid response from the caregiver. Appropriate antibiotics in appropriate doses should be begun promptly and tailored according to culture and sensitivity data. Once more, because of the chronic immunosuppression these infections can be fulminant.

Infection with *Pneumocystis carinii* is uncommon, since all programs institute prophylaxis post transplant with twice weekly Septra or the like.

Fungal infection or at least colonization is seen frequently. Aspergillus, Candida, and less commonly Nocardia and other pathogens are seen and should be looked for in unclear infectious scenarios. Bronchoscopic examination with cultures and biopsies, percutaneous needle biopsies or open lung biopsy may be necessary to establish the diagnosis. Oral antifungals are appropriate for colonization, whereas invasive infections are much more serious and often fatal.

Late airway complications

Airway complications are either stenosis or bronchomalacia in the late post-operative period. Stenosis can be seen after a known airway problem in the earlier post-transplant period, such as a partial dehiscence. At other times, the lesion can develop with no previous suggestion of trouble. It usually manifests with poor function and abnormal pulmonary function tests identifying airway obstruction. Bronchoscopy will make the diagnosis and treatment will be rigid bronchoscopy with dilation. Continued narrowing or recurrent problems can be managed with either silastic or expandable mesh wall stents. Both of these techniques have yielded satisfactory results for stenosis, although the disadvantage of the wall stents is that they cannot usually be removed. Both types of stents can be problematic because of colonization with infectious organisms and because patients may have difficulty raising secretions through them. The more difficult problem to manage is that of bronchomalacia. These ''floppy'' airways will lead to respiratory insufficiency because of their tendency to close during the respiratory cycle. Stenting is less successful since there is not a narrow area to grip the stent. When stenting is performed, mesh stents seem to be the better choice in this situation.

Bronchiolitis obliterans and bronchiolitis obliterans syndrome

As experience with isolated lung transplantation developed it became apparent that a percentage (probably 30–50%) of long-term survivors demonstrated a decline in pulmonary function, which was not due to acute rejection. This first manifested in a decline in objectively measured pulmonary function specifically a drop in forced expiratory volume in 1 second (FEV_1). This decline can be expressed as a percentage of the best FEV_1 obtained by the recipient in the post-transplant period. Transbronchial biopsies in such patients may not reveal the abnormality since the changes generally occur in the small airways. Sensitivity of transbronchial biopsy has been reported in wide ranges from 20% to 70%. Pathologically, the lesion progresses from a lymphocytic bronchiolitis with epithelial damage to evidence of scarring in the submucosa, which is presumably permanent. It is this scarring which becomes obliterative to small airways, which leads to the decline in function measured both subjectively by the patient and objectively by pulmonary function tests. The so-called bronchiolitis obliterans syndrome (BOS) is now defined based on FEV_1 determinations. This has been addressed in a working formulation to characterize and grade BOS [16]. The syndrome may remain stable but frequently can show a rapid downhill course and death by respiratory failure. Treatment strategies, none of which are reliably efficacious, include manipulation of immunosuppressive regimens, additional chemotherapeutic agents (e.g., methotrexate), and other approaches such as photopheresis. Multivariate analysis of large series of lung transplant recipients suggests that CMV infection, acute rejection, and lymphocytic bronchiolitis noted on lung biopsy are associated with an increased incidence of BOS. Therefore, management to avoid these, if possible, would make sense.

If BOS patients do not stabilize, then consideration of retransplantation becomes inevitable. A multi-institutional report suggests that reasonable results of retransplantation can be expected in ambulatory, nonventilated patients who are more than 2 years beyond their original transplant [17, 18]. Certainly the experience with other organs in retransplantation would suggest that it is a reasonable tactic. In long-term follow-up, this BOS accounts for most deaths and remains the Achilles' heel of lung transplantation.

Post-transplant lymphoproliferative disorder (PTLD)

The incidence, from pooled data, of this disorder is in the order of 7–8% (19). It is characterized by an abnormal B-cell proliferation ranging from benign polyclonal hyperplasia to full-fledged malignant lymphoma. The stimulus for this is Epstein–Barr virus (EBV). The highest incidence is in the first post-transplant year and in virus naïve recipients who are infected at the time of the transplant. Anti lymphocyte immunosuppression is also an important factor, increasing the incidence.

The disease presents usually as pulmonary nodules on chest x-ray, and because of difficulties in interpretation will usually require a generous open lung biopsy to confirm the diagnosis. Needle biopsies and small bronchoscopic biopsies are error-prone and should not be relied upon. Determination of EBV viral load is not yet a completely reliable diagnostic tool.

Treatment of the disorder is reduction of immunosuppression to allow native T-cells to repopulate and lower the viral infection. Anti B-cell CD20 monoclonal antibody (rituximab) has demonstrated efficacy. Antiviral therapy is only effective in the early viral replication phase, and is thus not efficacious once the disease is established.

The mortality of PTLD is high, in the 30–50% range. It is highest in the disseminated disease patients and better in patients where the disease is limited to the allograft [19].

Lung cancer

Lung cancer may develop in transplant patients with chronic obstructive pulmonary disease (COPD) or pulmonary fibrosis, both of which predispose to lung cancer. Malignancy may be identified unexpectedly in the recipient's lung removed during transplant, or may develop subsequently. Transplant performed as therapy for lung cancer, as has been attempted in patients with multicentric bilateral bronchoalveolar carcinoma has not been successful [20]. The development of lung cancer in the recipient carries with it an extremely high mortality.

Disorders associated with long-term immmunosuppression

The prolonged use of immunosuppressive agents in the lung transplant recipient carries with it a variety of well-recognized complication. Different

classes of immunosuppressive agents typically lead to a defined litany of disorders. These include osteoporosis [21], gastrointestinal complications [22], neurological complications [23, 24], and renal complications [25, 26]. A great deal of energy and time has been expended studying ways of avoiding these medication-induced complications.

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CHAPTER 10

Complications of Esophageal Resection

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Esophageal cancer is the eighth most common cancer and the sixth leading cause of cancer deaths worldwide [1]. Although the incidence of squamous cell carcinoma of the esophagus has declined in the Western World, the rates of adenocarcinoma of the distal esophagus and gastroesophageal junction have increased steadily. In 2007, 15 560 new cases of esophageal cancer were diagnosed in the United States with 13 940 deaths attributed to the disease [2]. Esophageal resection with or without preoperative therapy remains the mainstay of treatment. Despite significant advances in preoperative preparation, surgical techniques, and perioperative care, esophagectomy is a procedure associated with considerable morbidity. With advances in surgical technique and critical care, hospital mortality has significantly been lowered over the past decades with most high-volume centers reporting mortality less than 5% but morbidity remains in the 30–60% range [3–6].

Complications associated with esophageal resection can be divided into two groups: cardiopulmonary and technical. These range in severity from minor wound infections to life-threatening mediastinitis [7]. Intimate knowledge of each of the potential complications of esophagectomy leads to aggressive steps to either prevent or aggressively treat these complications at an earlier stage.

Hospital mortality

Several studies have shown that surgeon experience and hospital volume are inversely related to hospital mortality. Kuo *et al.* examined the outcomes of 1193 patients who underwent esophagectomy between 1992 and 2000 in Massachusetts. This study compared the three high-volume hospitals that performed 56.5% of all resections (674 of 1193) with 61 low-volume hospitals performing the remaining resections (519 of 1193). The average number of cases at low-volume centers was 1 esophagectomy per year. High-volume hospitals were associated with an almost fourfold decrease in hospital mortality (9.2% vs. 2.5%; $p < 0.001$) [3]. Analysis of the Surveillance, Epidemiology, and

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End Results (SEER), a Medicare-linked database, further supports these findings. Begg *et al.* analyzed the outcomes of over 5000 patients who underwent major oncologic surgery including esophagectomy, pneumonectomy, pancreatectomy, liver resection, or pelvic exenteration for patients between 1984 and 1993. Hospital volume was associated with lower mortality for esophagectomy ($p < 0.001$) and nearly all other procedures with the exception of pneumonectomy. Hospital mortality was over fivefold higher in low-volume centers in this study (17.3% vs. 3.4%, $p < 0.001$) [4]. Birkmeyer *et al.* reported similar findings in their analysis of surgical mortality in Medicare patients. In this study, 2.5 million surgical procedures performed between 1994 and 1999 were analyzed. Hospital volume per procedure was divided into quintiles and multiple regression techniques were used to describe relations between hospital volume and in-house 30-day mortality. Their findings were quite striking for the 6337 esophagectomy patients analyzed at 1575 hospitals. There was a 15% absolute difference in mortality between very low-volume hospitals (<2 procedures per year) and high-volume hospitals (>19 procedures per year), $p < 0.001$. The operative mortality decreased at each increase in quintile of hospital volume (lowest to highest: 23.1%, 18.9%, 16.9%, 11.7%, 8.1%, $p < 0.001$). The adjusted odds ratio (adjusted for age, sex, race, year of procedure, Social Security income, urgency of admission, and Charleston score) for operative mortality decreased from 1.0 to 0.36 from very low-volume to high-volume centers [5]. Other studies have confirmed these findings both at statewide as well as national level [6].

A possible advantage at high-volume centers is the development of standardized pathways for the pre and postoperative care of esophagectomy patients. These pathways formalize routine practices and form an infrastructure for patient care. They breed familiarity with the typical course of postoperative patients and help to identify outliers who may benefit from intensive nursing care or warrant more attention, thereby preventing or at least detecting complications early and mitigating their severity. Low *et al.* examined the outcomes of 344 consecutive patients who underwent esophagectomy for esophageal cancer in whom treatment was guided by perioperative clinical pathways. All patients were managed intraoperatively with a fluid restrictive resuscitation protocol with over 99.5% of patients being extubated immediately. Hospital mortality was 0.3% (1/344 patients) albeit with clinically significant morbidity in 45% patients [8]. These studies underscore the importance of institutional and surgeon experience in the proper management of complications from esophageal surgery.

Patient selection

General considerations

Several studies have attempted to identify specific preoperative risk factors. Bartels *et al.* retrospectively analyzed the records of 432 patients who underwent esophagectomy from 1982 to 1991 to identify risk factors correlated with

higher morbidity and mortality. Their analysis revealed four parameters: (i) Karnofsky performance index <80% ($p < 0.001$), (ii) aminopyrine breath test <0.4 ($p < 0.05$), (iii) vital capacity <90% ($p < 0.05$), and (iv) $PaO_2 < 70$ mm Hg ($p < 0.05$) [9]. A composite score based on these parameters and the cardiologist's impression of the patient's risk of cardiovascular mortality was used to create a composite score which was validated prospectively in 121 patients. In their prospective evaluation, mortality was significantly higher in 20 patients classified as high risk, 25%, compared to 101 patients classified either as low risk 2% ($p < 0.01$), or moderate risk 5% ($p < 0.05$) [9]. The authors subsequently changed their surgical practice to two-stage esophageal reconstruction for high or moderate risk patients with a resulting reduction in 30-day postoperative mortality to 1.6% from 7.4% in 252 consecutive patients from 1994 to 1996.

Schroder *et al.* evaluated this scoring system on 126 consecutive patients who underwent esophagectomy between January 1997 and December 2002. The preoperative risk was classified as "low" in 35 of 126 patients (27.8%), "moderate" in 67 of 126 (53.2%), and "high" in 24 of 126(19.0%). The overall morbidity and mortality were 54.8% (69/126 patients) and 5.4% (7/126). Postoperative morbidity was found to correlate with preoperative score [10]. Twenty-five of 35 patients (71.4%) with a "low" preoperative risk score had a "normal" postoperative course whereas only 16.4% of the patients with a "high" preoperative risk score had a similar classification ($p < 0.001$). Multivariate analysis revealed age (odds ratio (OR) 9.6, 95% confidence interval (CI) 2.6–32.7, $p = 0.001$), general status (OR 8.95, 95% CI 2.45–32.6, $p = 0.001$), and pulmonary function (OR 1.56, 95% CI 1.01–3.4, $p = 0.049$) as independent risk factors of postoperative outcome. This scoring system has been validated to provide a means of identifying high-risk patients and possibly redirecting their care to palliative measures such as esophageal stenting, photodynamic therapy (PDT), or radiotherapy [10]. However, rigid adherence to any scoring system would exclude some patients who would tolerate esophagectomy. Hence, these systems serve as guidelines and an individualized patient approach is advised.

Specific considerations

Many complications after esophageal resection may be prevented with proper patient selection, thorough preoperative evaluation and optimization of cardiopulmonary function. Adequately staged surgical candidates should undergo preoperative cardiac evaluation to identify risk factors for cardiovascular mortality and morbidity after esophagectomy. Patients deemed to be at high risk, such as those with new onset or unstable angina, exertional dyspnea, or limited exercise tolerance should undergo further evaluation with echocardiography, cardiac stress imaging, or occasionally cardiac catheterization. Interventions, if needed, such as myocardial revascularization, should be performed and esophagectomy delayed. Prophylactic use of beta-blockade or calcium channel blockers in elderly patients with peripheral vascular or

coronary artery disease may significantly reduce the incidence of postoperative arrhythmias. Swan–Ganz catheters can be useful for hemodynamic and fluid-status monitoring in high-risk patients. Pneumatic compression boots placement as well as the administration of subcutaneous heparin reduce thromboembolic complications and should be routinely started preoperatively.

Smoking cessation for as little as 2 weeks prior to esophagectomy improves mucociliary clearance and outcomes especially when combined with the use of incentive spirometry preoperatively [11]. Adequate postoperative analgesia using epidural catheters and patient-controlled analgesia decreases the incidence of pulmonary complications especially when a transthoracic esophagectomy is planned [12]. All patients should undergo a mechanical bowel clean out prior to surgery. Every patient should receive intravenous prophylactic antibiotics 30 minutes prior to the incision. Finally, patients undergoing esophagectomy should undergo jejunostomy tube placement for postoperative enteral nutrition in case anastomotic or other complications develop that would delay adequate oral alimentation.

General complications

Cardiovascular complications

Overall, the development of serious life-threatening cardiovascular complications is fairly low, occurring in 5–10% of patients [13–15]. The most common complication is supraventricular tachycardia, commonly atrial fibrillation, which occurs in 15–25% of patients typically within 48–72 hours of surgery [13–18]. Several studies have demonstrated that the perioperative use of antiarrhythmic agents or atrioventricular nodal blocking agents, such as beta-blockers and calcium channel blockers, reduces the incidence of atrial fibrillation in patients undergoing thoracotomy [16, 19]. Regardless of the surgical access (transthoracic or transhiatal), esophagectomy patients benefit from these agents in preventing atrial fibrillation. A small retrospective study presented only in abstract form evaluated the use of amiodarone 200 mg BID given immediately postoperatively for prophylaxis against atrial fibrillation after esophagectomy. One of eight patients on amiodarone developed atrial fibrillation compared to 5 out of 24 patients in the control group (12.5% vs. 31.2%, $p = 0.32$) [20].

Given the benefit of beta-blocking agents of reducing cardiovascular mortality in thoracic surgery, beta-blockers have become the first line drug of choice in many centers for not only atrial fibrillation prevention but also decreasing overall cardiovascular morbidity and mortality [21]. The widespread application of the use of beta-blockers is due to several studies with particular attention to the study by Lindenauer *et al*. [21] who conducted a retrospective propensity-matched analysis of 782 969 patients undergoing noncardiac surgery. Of these, 663 635 (85%) had no contraindications to beta-blockers with 122 338 (18%) receiving beta-blocker treatment during the first 2 hospital days.

Patients were risk stratified for cardiovascular morbidity using the Revised Cardiac Risk Index (RCRI). In their propensity-matched analysis, beta-blocker treatment effect on risk of death was inversely proportional to RCRI score. In those patients with a RCRI score of 0 or 1, there was no benefit to beta-blocker treatment. For those with RCRI scores of 2, 3, 4, or more, the adjusted odds ratios for death in the hospital were progressively reduced (0.88, 0.71, and 0.58; $p < 0.05$), respectively [21]. Although 70% of patients had orthopedic or abdominal operations and only 7% underwent thoracic procedures, the results of this study have been widely applied. Current American Heart Association (AHA) guidelines recommend beta-blockers for patients with more than minimal risk of cardiovascular complications in the perioperative period [22].

Calcium channel blockers have also shown efficacy in preventing cardiovascular complications in patients undergoing thoracic procedures. Amar *et al.* conducted a randomized, double-blind, placebo-controlled study of 330 patients to ascertain the effect of dilatizem on atrial fibrillation after pulmonary resection. Postoperative atrial arrhythmias occurred in 25 (15%) of the 167 patients in the dilatizem group and 40 (25%) of the 163 patients in the placebo group ($p = 0.03$). Dilatizem reduced the incidence of arrhythmias by 50% [16]. However, calcium channel blockers do not reduce perioperative mortality and are not recommended by the AHA as first line agents in patients who can tolerate beta-blockade [22]. Based on these studies, our first line perioperative medication of choice to prevent cardiovascular complications is beta-blockers for all patients with no contraindication to their use.

Pulmonary complications

The incidence of pulmonary complications after esophagectomy is high regardless of approach. Complications include pneumonia, atelectasis, aspiration, and respiratory insufficiency requiring prolonged intubation. The incidence of these complications ranges from 20% to 50% at most large volume centers. As a high proportion of esophageal cancer patients are malnourished and/or have an extensive smoking history, this is not unexpected [15, 23–26]. Pneumonia may in fact be responsible for many of the deaths occurring after esophagectomy [15, 25]. Atkins *et al.* in a retrospective analysis of 379 esophagectomies found pneumonia to be associated with a 20% chance of death ($p = 0.0008$) [25]. In a retrospective study of 61 patients, Avendano *et al.* attempted to identify preoperative risk factors for pulmonary complications. Preoperative factors that inversely correlated with the need and duration of mechanical ventilation, as well as for prolonged length of stay included: preoperative chemoradiotherapy ($p = 0.02$), forced vital capacity (FVC) ($p = 0.01$), and forced expiratory volume in 1 second (FEV_1) ($p = 0.02$) [24]. In another retrospective analysis, Ferguson *et al.* analyzed 292 patients who underwent esophagectomy for malignancy between 1980 and 2000. Pulmonary complications developed in 78 (27%) patients and were associated with a 4.5-fold increase in operative mortality (7–32%). Multivariate analysis identified increasing patient age (OR 1.31, 95% CI 0.99–1.74, $p = 0.059$) and forced expiratory

volume in 1 second (OR 1.21, 95% CI 1.07–1.38, $p = 0.0003$) as risk factors for pulmonary complications. A scoring system based on these factors and performance status was developed which predicted increased risk of pulmonary complications ($p = 0.013$). Other studies have confirmed age and poor preoperative FEV_1 as risk factors for pulmonary complications [14]. Pulmonary function tests, hence, can help identify those who may need increased vigilance postoperatively. Smoking cessation even for a short period prior to operation improves mucociliary clearance especially when combined with the use of incentive spirometry preoperatively [11]. Adequate postoperative analgesia using epidural catheters or patient-controlled analgesia is critical in improving patient compliance with postoperative pulmonary hygiene and decreases the incidence of pulmonary complications after esophagectomy [12].

Prevention of aspiration and control of pulmonary secretions is paramount in preventing postoperative pneumonia and other respiratory complications. Patient should have their head of bed elevated at all times with a functioning naso-conduit tube for decompression of the esophageal substitute. Protocol-driven pathways in which patients undergo early ambulation, aggressive pulmonary hygiene with routine frequent chest physiotherapy, nasotracheal suctioning and, if needed, bronchoscopy to aspirate pulmonary secretions decrease pulmonary complications [26]. Swallowing evaluation prior to the institution of an oral diet identifies those at risk of aspiration and further prevents pneumonic complications [26]. In those developing pneumonia and requiring mechanical ventilation, tracheostomy is favored after 10 days of intubation to facilitate pulmonary toilet. However, prevention of pulmonary complications by early identification of those at risk and early intervention cannot be overemphasized.

Thromboembolic disease

Thromboembolic disease is a significant source of postoperative morbidity in oncologic patients undergoing surgery; however, the exact incidence of thromboembolic complications in patients undergoing esophageal resection is unknown [27]. A Japanese study reported an overall incidence of pulmonary embolism (PE) of 2.6% (26/1032) over a 13-year period. The incidence of PE decreased from 3.2% to 0.7% after the institution of subcutaneous heparin and pneumatic compression boots. A British study of 127 esophagectomy patients reported a rate of deep venous thrombosis (DVT) rate of 1.6% in patients without prophylaxis [28]. This stands in contrast to data pooled from general surgical patients where rates of DVT and PE were as high as 29% and 1.6%, respectively, in those with malignant disease [27]. The lower incidence of DVT reported in the British study may be due to inadequate detection from suboptimal screening methods. Patients undergoing esophagectomy are considered at high risk for developing DVT and PE and should receive preoperative prophylaxis [27, 29]. Preventive regimens include the use of intermittent compression boots and/or low dose unfractionated heparin or low molecular weight heparin (i.e., enoxaparin, dalteparin, etc.). Low molecular weight heparin is

at least as safe and effective as unfractionated heparin. Its advantages include its convenient once daily dosing regimen. Combined regimens of pneumatic compression boots and heparin therapies may be superior to single agent therapy as has been shown in cardiac and colorectal surgery patients [29, 30].

Complications associated with esophageal resection

Hemorrhage

Hemodynamically significant bleeding can be caused intraoperatively by inadvertent injury to vascular structures both intrathoracic and intraabdominal. Commonly injured structures include the short gastric vessels and azygous venous system. Other structures less commonly injured, but when injured lead to significant consternation, include the aorta and the inferior pulmonary vein. Intraoperative vascular control often requires additional exposure through additional incisions, such as a rapid right thoracotomy for azygous or inferior pulmonary vein injury.

Delayed bleeding within 24 hours of surgery can be due to a variety of sources but typically short gastric or bronchoesophageal vessels whose ties, clips, or staples may have slipped. Hemodynamically significant bleeding with a decreasing hemoglobin and obvious signs of intraabdominal or intrathoracic bleeding (abdominal distention, persistent chest tube output, etc.) warrant prompt return to the operating room for re-exploration. Patients with long-standing achalasia often have large aortic perforators to the esophagus and bleeding from these vessels is not readily controlled by mere packing [31, 32].

Anastomotic leak

Anastomotic dehiscence is one of the most serious postoperative complications, which historically was associated with considerable mortality. The incidence and severity of this complication is variable and based on the type of conduit, location of the anastomosis, and the patient's preoperative functional and nutritional status. Technical determinants of anastomotic integrity include a tension-free anastomosis, a well-vascularized conduit, adequate tissue quality, and surgeon's experience. Although there are no significant difference in anastomotic leak rate between circular stapled and hand-sewn anastomoses, recent reports suggest that a hybrid anastomosis using a linear stapler for the back wall and a running suture for the front wall may have a lower leak rate [33, 34].

Generally, cervical anastomoses have a higher leak rate likely due to subclinical vascular insufficiency in the conduit but lower mortality and morbidity since leaks are usually adequately treated by drainage through the cervical incision with minimal adverse sequelae. In contrast, thoracic anastomotic leaks lead to mediastinitis and sepsis requiring targeted chest tube drainage or occasionally thoracotomy and wider surgical drainage. In a meta-analysis

by Muller *et al.*, the anastomotic leak rate was significantly lower for thoracic versus cervical anastomosis (11 ± 6% vs. 19 ± 15%) but mortality was significantly higher after intrathoracic reconstruction (69 ± 16% vs. 20 ± 11%) [35]. However, this report by Muller *et al* reflects outcomes of surgical practice throughout the 70s and 80s and is not representative of current surgical results. For example, Lam *et al.* found no difference in anastomotic leak rate (4.3% vs. 3.7%, p = NS) or associated mortality (40% vs. 36%, p = NS) in 411 prospectively analyzed patients who underwent esophageal resection with either cervical or thoracic anastomoses at a single institution. Similarly, recent series of esophagectomies with transthoracic anastomoses have also reported mortality rates associated with anastomotic dehiscence below 10% [36–38].

Most anastomotic leaks manifest within 10 days postoperatively. Anastomotic leaks present in a myriad of ways from clinically silent, detected only on barium esophagrams, to fulminant sepsis. Urschel usefully categorized anastomotic leaks into four groups according to clinical presentation and outcomes [39]. The first group includes those with conduit necrosis which typically occurs within 48 hours. Patients present with septic shock and often-purulent chest or neck drainage. Suspicion of a nonviable conduit requires prompt diagnosis and intervention. Radiographic studies, including chest CT, are not always helpful or possible in unstable patients. Diagnosis is made by endoscopic examination of the conduit if necrosis is suspected or at the time of surgical re-exploration. At the time of re-exploration, all nonviable portions of the conduit must be resected and the viable remnants retrieved into the abdominal cavity and oversewn. Proximal diversion is accomplished with the creation of a stoma. A high index of suspicion with early endoscopy and prompt re-exploration can prove lifesaving for an otherwise fatal complication.

The second group consists of patients with clinically apparent intrathoracic leaks. These patients present with fever, pneumothorax, and/or pleural effusion. The principals of proper management of thoracic leaks include adequate drainage of the pleural space, control of the anastomotic leak/fistula, and re-expansion of the lung to obliterate the pleural space. This is usually accomplished with simple or image-guided chest tube placement. Persistent sepsis, loculated undrained fluid collections or incomplete lung expansion should prompt surgical exploration for decortication and wider drainage. At that time a buttressed repair of the leak may be attempted or alternatively a T-tube may be placed through the leak and exteriorized to create a controlled fistula. Newer approaches to control intrathoracic leaks include CT-guided drainage of the pleural space with resultant control of the leak and/or stent placement to seal the leak [40–43]. Griffin *et al.* reported the outcomes of 13 patients who had an intrathoracic anastomotic leak after esophagectomy that were all managed successfully with radiologically guided drainage and supportive therapy [43]. Other small series report success with similar methods for isolated anastomotic leaks [42]. Kaur *et al.* reported the endoscopic treatment of thoracic esophageal leaks in 12 patients (out of 269 patients who underwent esophagectomy). Ten patients underwent insertion of a covered

metal stent and two patients were treated with fibrin glue placement. All patients had successful outcomes with closure of the anastomotic leak; although one patient required stent repositioning for leak/fistula closure [41]. Similar results with endoscopic stenting have been reported by other groups as well [44–46]. Stents are removed once the fistula/leak has sealed. Stent removal may be facilitated by the use of polyester stents [44, 46].

Most series describing CT-guided or endoscopic control of anastomotic leaks have been small and the utility and general applicability of endoscopic stenting and radiologic drainage of thoracic anastomotic leaks are uncertain. They may be an option in those unfit for surgery or in patients in whom surgical re-exploration and repair have failed. In support of stenting as an option, Tuebergen *et al.* reported the results of 32 patients with an intrathoracic esophageal leak (esophagectomy ($n = 19$)–(thoracoabdominal ($n = 17$) transhiatal ($n = 2$)), transhiatal gastrectomy ($n = 3$), laparoscopic fundoplication ($n = 2$), iatrogenic or spontaneous perforation ($n = 8$)) who were treated by stent placement. Eighteen of these patients had failed surgical closure prior to stent placement. A near 80% success rate was reported for this group where a high proportion had failed surgical repair [45]. Although clearly not traditional therapy for thoracic anatomic leaks, endoscopic stenting and image-guided drainage must be kept in mind as viable options.

The third group categorized by Urschel consists of cervical leaks. Cervical anastomotic leaks present as wound erythema and crepitus with associated fever and leukocytosis. Initial management consists of opening the cervical incision to drain the leak. Cervical leaks typically close with time and proper wound care. In a subset of patients, the cervical anastomosis slips into the mediastinum and causes mediastinitis with resulting sepsis. If this occurs, a more aggressive approach is required as described for thoracic anastomotic leaks [47]. Stent placement for cervical anastomotic leaks has been described but the utility is limited as open wound drainage is typically successful [48].

The fourth group described consists of clinically silent cervical or thoracic anastomotic leaks. In these situations, patients are asymptomatic with no laboratory or clinical signs of infection, but have leaks found by radiologic studies in which the leak is contained by surrounding tissues and often internally drains back into the conduit. Management of these contained anastomotic leaks consists of observation with the patient maintained on jejunostomy feedings until further radiologic studies demonstrate healing of the leak. Any signs of deterioration warrant intervention. Contained leaks near the aorta or trachea may warrant intervention to prevent fistula formation [49–51].

Anastomotic stricture

Patients with anastomotic stricture after esophageal resection present with dysphagia. Stricture formation may start as soon as 4–6 weeks after surgery. The incidence of anastomotic stricture varies in series from 5% to 40% and is

related to ischemia at the anastomosis and inflammatory changes associated with wound healing [31, 32, 52, 53]. Hence, ensuring a tension-free anastomosis with an adequate blood supply may prevent anastomotic stricture formation, especially the delayed variety which presents months after resection. Constructing a meticulous anastomosis also aids in preventing leaks which have been shown to increase the risk of anastomotic stricture formation, likely from the ensuing exaggerated inflammatory response to injury [54]. Reflux esophagitis can also lead to stricture formation. Following dilation, high dose acid suppression medications may aid in preventing recurrence in these patients. Severe reflux and recurrent stricture rarely requires revisional surgery. Anastomotic stricture remote from the time of surgery should also heighten concerns for recurrent carcinoma. A careful workup is warranted including CT-PET and endoscopy with or without endoscopic ultrasound (EUS) and biopsies.

Treatment of benign strictures, especially early strictures, is usually successful with endoscopic wire-guided balloon, Savory or Maloney dilatation. Recalcitrant strictures may require short-term or occasionally long-term stent placement [55, 56]. Stent placement in most cases of recurrent strictures do not provide long-term solutions but temporize matters and increase the length of time between interventions [56]. Recurrent benign strictures occasionally need resection for permanent resolution of dysphagia. However, re-resections are technically demanding endeavors that may not be successful. Given their rarity, there is no large series describing their outcomes. Malignant strictures can be treated by resection in those with isolated disease, which as noted is technically demanding [57]. Palliative measures such as radiation therapy, stents, and PDT are employed for those with distant disease or who are poor surgical candidates [58].

Tracheobronchial injury with fistulization

Tracheobronchial injury leading to postoperative esophageal conduit to bronchial fistulas is an uncommon complication [51, 59]. Injuries to the membranous airways have been described after both transthoracic and transabdominal esophagectomies. These injuries can be due to blunt trauma, traction injury, or thermal cautery injury to the major airways during esophageal mobilization or mediastinal lymph node dissection. Rarely airway injury results from double lumen endotracheal or bronchial blocker placement for lung isolation. Injury noted intraoperatively should be repaired and buttressed with intercostal muscle or pleura [51, 59]. Unrecognized small injuries may heal without consequence or progress to fistulization into the esophageal conduit resulting in tracheobronchial-gastric/colonic fistulization. Treatment consists of immediate buttressed repair with intercostal muscle or pleura with or without diversion through a thoracotomy in patients developing sepsis [60, 61]. Bronchial and esophageal conduit stent placement has been successful in some cases [62–64].

Chylothorax

Chylothorax due to thoracic duct injury is seen after both transthoracic and transhiatal esophagectomy. The incidence of this complication ranges from 1% to 5% and is poorly tolerated in esophageal cancer patients who are often nutritionally depleted [65–68]. Chylothorax presents with persistently high chest tube output that increases with enteral alimentation. The fluid becomes milky in character with fatty enteral intake. Diagnosis, in uncertain cases, is confirmed by fluid analysis with chyle having elevated levels of triglycerides, chylomicrons, and a cell count rich in lymphocytes. Pleural fluid with a triglyceride level >110 mg/dl has a >99% chance of chylothorax, whereas levels <50 mg/dl has less than 5% chance [66].

Prevention of chylothorax requires intimate knowledge of the thoracic duct anatomy. Beginning in the abdomen at the cisterna chili, the duct enters the thorax at the aortic hiatus anterior to the vertebral bodies and posterior to the aorta. It then ascends in the right hemithorax between the anterior surface of the vertebral bodies between the aorta and azygous vein. At the level of the carina, the duct crosses to the left side and passes behind the aortic arch and into the neck where it passes behind the carotid sheath and drains into the junction of the left jugular and subclavian veins. However, the course of the thoracic duct is highly variable and the standard pattern described above occurs in less than half of patients. Injury to the duct along its pathway can lead to chylothorax [69]. Intraoperative identification of injury mandates repair of injury if possible or mass ligation of the duct at the hiatus.

Postoperative management of chylothorax after esophagectomy is controversial. Conservative management consists of total parental nutrition with or without fat-restricted oral diets with medium chain triglyceride-based enteral formulas. The efficacy of octreotide in controlling chyle leaks is uncertain [70, 71]. Conservative management is effective in controlling and effectively sealing chyle leaks in 70–80% of patients within 4 weeks postoperatively. This approach, however, is associated with nutritional depletion and septic complications [54, 68, 72, 73]. Surgical intervention entails repair/ligation of the injury if found or mass ligation of the duct at the hiatus via a right thoracotomy or right video-assisted thorascopic (VATS) approach. Ligation of the duct intraabdominally at the hiatus is possible as well. The administration of cream at 24 hours prior to surgical exploration often aids in identification of the duct. Early (5–7 days) surgical ligation is highly effective and is our preferred treatment strategy.

In an attempt to identify risk factors for failure of conservative management of postesophagectomy chylothorax, Dugue *et al.* examined 23 patients after transthoracic esophagectomy who developed chylothorax [65]. Retrospective analysis revealed only one statistically significant factor in identifying those who failed conservative management: chylous chest tube drainage >10 mL/kg on postoperative day 5 was present in all patients who required reoperation with only two patients with chylous drainage <10 mL/kg requiring intervention ($p < 0.001$) [65]. Based on these results, any patient with

persistent chylous output greater than 10 mL/kg on postoperative day 5 should be explored.

Thoracic duct embolization by interventional radiology techniques has been described as a means of controlling chylothorax. Patients are initially mapped with a lymphangiogram, which defines their cisterni chyli. The cisterni is then accessed transabdominally using percutaneous catheter-based techniques and either embolized with coils and fibrin glue or fenestrated so that the chyle is drained internally into the peritoneal cavity and absorbed. Embolization is typically more effective than fenestration [74–77]. These techniques are time consuming and require the patient to lay still in the interventional suite for long periods of time and hence not suited for those at risk of aspiration. However, they do offer an attractive option in patients who remain marginal after esophagectomy and are unlikely to tolerate further surgery. Success rates vary with center experience and range from 50% to 80% [74–77].

Injury to the laryngeal nerve

Recurrent laryngeal nerve injury is a source of significant postoperative morbidity. The recurrent laryngeal nerve innervates the intrinsic muscles of the larynx (except for the cricothyroid) as well as receiving sensation from the mucous membrane below the vocal cords. Hence, recurrent nerve injury impairs laryngeal sensation in addition to affecting the patient's voice by causing hoarseness. Nerve injury impairs the ability to generate an effective cough and thereby impairs postoperative pulmonary toilet predisposing patients to life-threatening aspiration with concomitant pneumonia. Diagnosis is suspected by assessing the quality of the voice after postoperative day 2 as cord edema from perioperative intubation may lead to some degree of medialization and mask the degree of hoarseness and hence injury. Confirmatory studies include direct fiberoptic assessment or video-assisted swallow studies.

Recurrent nerve injury occurs in 3–40% in patients undergoing esophageal resection [23, 26, 31, 78–80]. Rates are reportedly higher with extended en bloc esophagectomy techniques, as high 30–45% in some series [79, 80]. This is not universally true as Altorki *et al.* reported only a 6% incidence [23, 81]. Recurrent nerve trauma occurs most frequently during cervical dissection in the neck or high in the thoracic inlet during three-field lymphadenectomy within the right chest. Several steps can be taken to prevent injury including: (i) keeping the plane of dissection on the esophagus when dissecting the esophagus within the tracheoesophageal groove, (ii) avoiding metal retractors or forceps within the tracheoesophageal groove, and (iii) using a no touch technique when dissecting the nerve [7, 23, 26, 31, 78–80].

Prompt diagnosis is required if injury is suspected followed by equally expeditious treatment. Treatment consists initially of temporary medialization with Gelfoam. If long-term recovery does not occur, permanent medialization with a prosthesis is performed. Patients are not fed until medialization performed and their swallowing evaluated postmedialization by a trained experienced speech therapist or video fluoroscopically.

Diaphragmatic herniation

Abdominal viscera can herniate through the enlarged esophageal hiatus after esophagectomy. This diaphragmatic herniation is a rare complication after esophagectomy with an estimated incidence of 2–4% [82, 83]. The incidence seems to be similar for esophagectomy utilizing minimally invasive techniques [84]. The herniation may occur acutely within a week after surgery but typically occurs several weeks to months after esophagectomy. The exact etiology of these hernias is unclear. However, it is clearly related to manipulation of the esophageal hiatus. Tacking the conduit to the hiatus circumferentially may aid in preventing this complication. As many of these herniations occur next to the conduit by the divided left crus, leaving it intact may prevent subsequent herniation [84].

Patients with herniated viscera are typically asymptomatic but may experience vague episodic upper quadrant or lower thoracic pain. If mechanical obstruction ensues, nausea, vomiting, and cramping pain predominate necessitating prompt intervention. Diagnosis is made with upper gastrointestinal imaging or chest and abdominal CT. As there is an inherent risk of obstruction and strangulation, these hernias need to be surgically corrected [82–84].

Delayed gastric emptying and dumping syndrome

A minority of patients, up to 10% in some series, develop clinically significant gastric emptying problems after esophagectomy [85–88]. A variety of factors have been implicated including vagotomy, torsion of the stomach in the right chest, compression of the distal gastric conduit at the hiatus, gastric conduit size, and a lack of an accompanying drainage procedure (i.e., pyloroplasty or pyloromyotomy). Patients with intrathoracic anastomoses are prone to develop emptying problems due to the redundant stomach above the diaphragm [37]. Delayed gastric emptying puts patients at increased risk of aspiration pneumonia and subsequent respiratory compromise.

Preventive measures include ensuring an adequate size at the diaphragmatic hiatus to prevent conduit compression and performing a gastric drainage procedure. However, the utility of prophylactic pyloroplasty and pyloromyotomy is controversial [85, 87–92]. In a prospective randomized trial of 72 patients who underwent transthoracic esophagectomy with or without pyloroplasty, Cheung *et al.* found no complications resulting from pyloroplasty and no statistically significant difference in symptoms of poor gastric emptying at 6 months or at 2 years [89]. Given the low morbidity associated with pyloroplasty and the inability to identify risk factors for poor gastric emptying, the authors concluded that pyloroplasty is reasonable to perform. In a meta-analysis of nine randomized-controlled trials encompassing 553 patients who underwent esophagectomy, Urschel *et al.* found no difference in operative mortality, anastomotic leak rate, pulmonary complications, or fatal aspiration rate between those who underwent pyloric drainage procedures or not

[92]. Complications associated with gastric emptying procedures were low as well [92]. Given the low complication rate associated with gastric drainage procedures, prophylactic pyloromyotomy or pyloroplasty is in our opinion reasonable for all patients undergoing esophagectomy in order to avoid potential life-threatening complications.

Immediate delayed gastric emptying in the postoperative period may be due to mucosal edema at the pyloromyotomy or pyloroplasty. Edema typically resolves in 10–14 days. Persistent delayed gastric emptying after 14 days may be improved with prokinetic agents such as metoclopramide or erythromycin [86, 93]. If an incomplete pyloromyotomy or no gastric drainage procedure was performed, endoscopic balloon dilatation of the pylorus or surgical drainage should be performed without delay [88].

Patients with dumping syndrome have sweating, palpitations, nausea, and epigastric distention following meals. The vasomotor symptoms are thought to occur secondary to the rapid transit of hyperosmolar gastric contents into the jejunum, which causes rapid hyperglycemia followed by reactive hypoglycemia. Gastric emptying procedures can contribute to rapid gastric emptying which is why this procedure is controversial. Symptoms usually abate with time and can be improved by dietary modifications including taking multiple small meals, avoiding liquids during meals, avoiding milk products, and meals in high in carbohydrates [7].

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CHAPTER 11

Complications of Minimally Invasive Esophagectomy

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Introduction

The incidence of adenocarcinoma is rising rapidly in the Western population in the last two decades [1]. Esophagectomy with or without neoadjuvant or adjuvant therapy is the standard treatment for early stage or locally advanced esophageal cancer. However, esophagectomy is a complex operation with a potential for significant morbidity and mortality. One study showed that the mortality in the United States varied from 8% to 23% depending on whether the surgery was performed in a high- or low-volume hospital [2]. We have adopted a minimally invasive approach in an effort to decrease the risks, while preserving the oncologic benefits of esophagectomy [3]. While many of the complications after minimally invasive esophagectomy (MIE) and their treatment are common to the open approach to esophagectomy, this chapter will in addition, focus on some of the special aspects of the minimally invasive approach. We summarize the technical aspects of the operation, patient selection, pitfalls to avoid, and the incidence, prevention, and treatment of complications following MIE.

Minimally invasive surgical training and patient selection

Unlike an open esophagectomy, during MIE, the dissected tissue is not directly palpated by the hand, but by the instruments, and is visualized on the monitor. The surgeon needs to adapt to this situation and can no longer rely upon hand–mind–hand or hand–eye coordination [4]. In order to perform a complex operation in a minimally invasive fashion, advanced training is necessary for the development of these skills and is essential for the avoidance of complications, the successful completion of the procedure, and in optimizing outcomes.

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Patient selection

Proper patient selection is critical to optimize results. This is particularly important when one is learning to perform MIE. It is important to start with early stage tumors or patients with high-grade dysplasia, avoid patients with more advanced tumors, and those who have undergone neoadjuvant therapy. As one gains experience, more advanced tumors or complex operations can be undertaken. This approach helps the surgeon avoid complications when adopting a minimally invasive approach.

Staging

Proper staging is critical to select patients appropriately and enroll patients in clinical trials [5, 6]. We recommend an endoscopic ultrasound (EUS) in all patients, and positron emission tomography (PET) scan when possible. Further minimally invasive staging, in particular laparoscopy, is valuable in detecting unsuspected metastases to the liver or peritoneum and can be more accurate compared to PET scans or EUS [7, 8]. We perform laparoscopy or thoracoscopic staging when there is concern for a T4 lesion, or metastases.

Technique of minimally invasive esophagectomy

Our original approach was a combined laparoscopic and thoracoscopic approach with a neck anastomosis [3]. We have moved to an Ivor–Lewis approach with a right chest anastomosis [9]. The steps of the operation are similar with difference being the sequence of laparoscopy and thoracoscopy. In the Ivor–Lewis approach, the surgery is started with a laparoscopic approach, and subsequently the thoracoscopic portion of the operation is performed with the anastomosis in the chest. This is our preferred approach as long as the chest anastomosis is oncologically sound and does not compromise margins.

Some of the important steps of MIE are highlighted below.

Esophagogastroduodenoscopy

We start with an on-table endoscopy to assess the extent of involvement of the gastroesophageal junction, cardia, and the stomach. This helps in planning the surgical resection margins, and also to plan the site of anastomosis. For example, a tumor with more subcardial extension may require a more extensive resection in the abdomen, and will necessitate the anastomosis to be performed in the chest, rather than in the neck. Similarly, in a patient with Barrett's esophagus and high-grade dysplasia, the extent of the high-grade dysplasia (HGD) should be assessed preoperatively. While the distal extent of the resection may not be problematic, extension very proximally may require a high proximal resection margin and anastomosis in the neck. Therefore, esophagogastroduodenoscopy (EGD) is a critical and important first step to avoid problems in terms of resection margins and to plan the surgery. It is

important to limit insuffalation with air since this will interfere with subsequent laparoscopic surgery. The stomach is decompressed prior to removal of the endoscope.

Laparoscopic phase

We start the operation with the laparoscopic exploration in patients where an Ivor–Lewis–Tanner anastomosis is planned. Proper port placement is critical. There should be some flexibility in the port placement to suit the body habitus of the patient, and to account for prior surgery. Similar to other laparoscopic surgeries, avoidance of inadvertent injury to abdominal viscera during port placement is important.

The patient is positioned in steep reverse Trendelenburg. A total of five abdominal ports (four 5 mm and one 10 mm) are used for the dissection (Figure 11.1). The first port, the 10-mm port, is placed with a cut down technique, and subsequent ports are placed under direct visualization. An initial exploration is performed prior to starting the gastric mobilization.

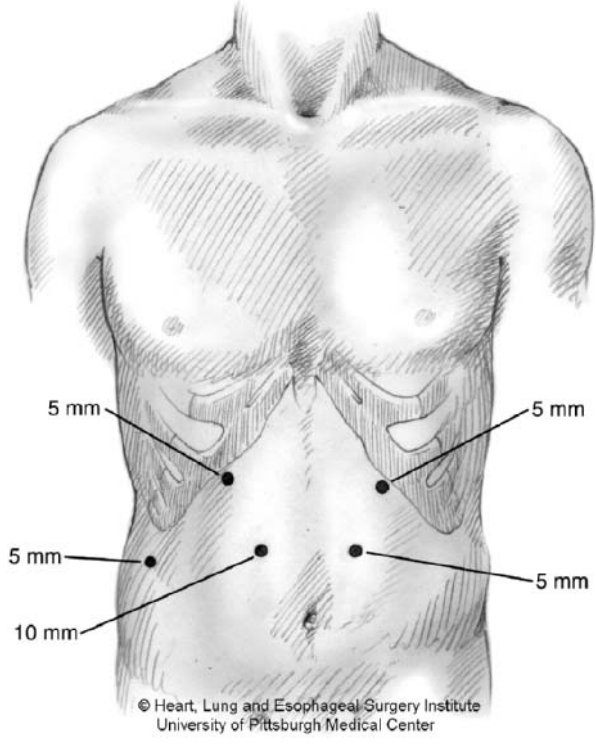

Figure 11.1 The location of the abdominal ports is depicted in this diagram.

Gastric mobilization

The dissection is started with the division of gastrohepatic ligament. The right and left crura of the diaphragm are then dissected. We avoid dividing the phrenoesophageal membrane which may lead to loss of pneumoperitoneum. The stomach should be handled with extreme care. The greater curvature of the stomach is mobilized by dividing the short gastric vessels using ultrasonic coagulating shears. The gastrocolic omentum is then divided with care taken to preserve the right gastroepiploic arcade. During this portion of the dissection, we mobilize and preserve a well-vascularized omental flap to use as a buttress of the intrathoracic anastomosis. The stomach is retracted anteriorly, and the posterior attachments are divided. A complete celiac node dissection is performed prior to division of the left gastric vessels with a vascular stapler. It is important to recognize and spare an aberrant left hepatic artery should it be present. A pyloroplasty is performed and buttressed with an omental flap.

Construction of the gastric tube

This is a critical component of the procedure. Too narrow a tube leads to ischemia and a high leak rate [3]. We create an approximately 5-cm gastric tube, starting at the lesser curve. We preserve the right gastric vessels, although these can be divided if needed. We start with the 4.8-mm stapler (Endo-GIA II, Covidien, Norwalk, CT), beginning in the lesser curve, proximal to the pylorus. It is important to avoid excessive manipulation and trauma to the gastric conduit during this step. To facilitate exposure, an assistant gently retracts the fundus (which we ultimately discard) of the stomach superiorly, and another assistant gently retracts the pyloroantral area inferiorly (Figure 11.2). This facilitates proper alignment, and construction of the gastric tube with uniform diameter.

A jejunostomy tube is then placed. The jejunum is secured to the anterior abdominal wall about 3 cm distal to the jejunostomy tube site to prevent torsion. The final step is division of the phrenoesophageal membrane, with partial division of the crura. Steps to avoid diaphragmatic hernia or obstruction at the level of the hiatus are described later.

Thoracoscopic phase

Thoracoscopic port placement

The patient is then positioned in the left lateral decubitus position. Four thoracoscopic ports are typically used. More recently, we have added a 5-mm port anteriorly which the second assistant uses intermittently for suction (Figure 11.3). A 10-mm camera port is placed at the seventh to eighth intercostal space, just anterior to the midaxillary line. A 10-mm port is placed at the eighth or ninth intercostal space, posterior to the posterior axillary line, for the ultrasonic coagulating shears. A 10-mm port is placed in the anterior axillary line at the fourth intercostal space, and this is used to pass a fan-shaped retractor to retract the lung anteriorly and allow exposure of the esophagus. A 5-mm

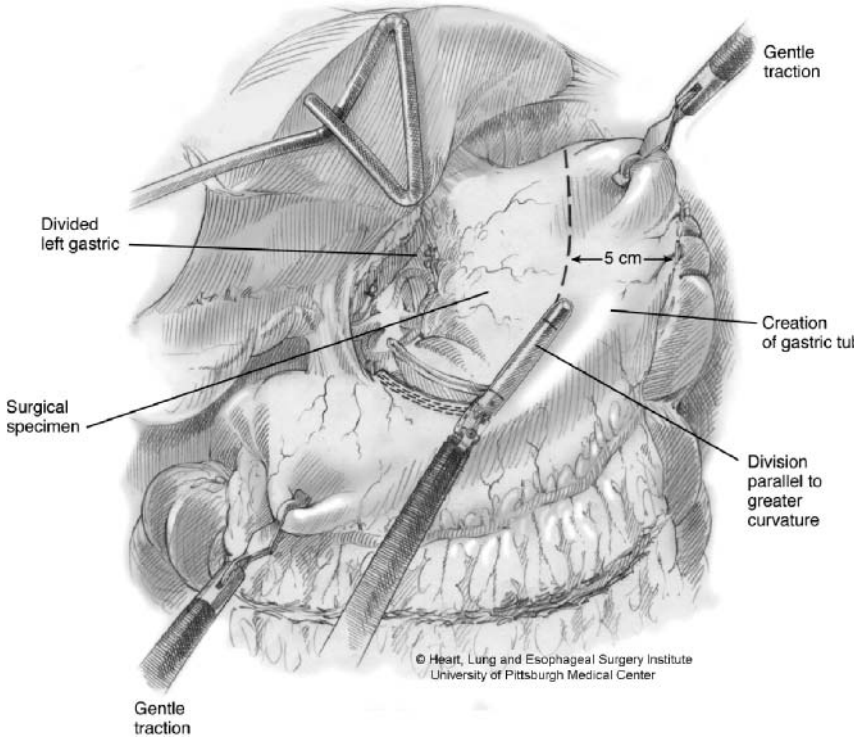

Figure 11.2 The creation of a 5-cm gastric tube is depicted in this diagram.

port just posterior to the scapula tip is used for instruments for retraction and counter traction. Ultimately, the eighth posterior interspace port is enlarged to 5 cm to enable passage of the end-to-end stapler and removal of the specimen. After initial thoracoscopic exploration, we start the procedure with a single retracting suture which is placed near the central tendon of the diaphragm and brought out through the chest wall through a 1-mm skin incision. This allows downward traction on the diaphragm, and aids exposure of the distal esophagus.

Esophageal mobilization

Next, the inferior pulmonary ligament is divided. The mediastinal pleura overlying the esophagus is divided up to the level of the azygos vein to expose the thoracic esophagus. An endoscopic vascular stapler is used to divide the azygos vein. The esophagus along with the periesophageal tissue and lymph nodes is circumferentially mobilized from the diaphragm to the level of 1–2 cm above the carina. We utilize the ultrasonic coagulating instrument for the dissection, and endoscopic clips are applied generously for larger vessels and any lymphatics. A Penrose drain is placed around the esophagus to facilitate traction and exposure.

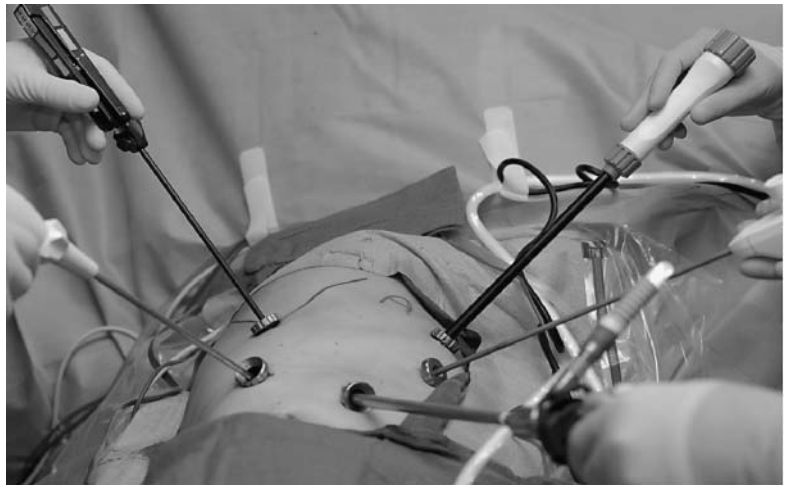

Figure 11.3 The location of the thoracoscopic ports is shown in this picture.

The plane of dissection is directly on the esophagus above the azygos to prevent injury to the airway and the recurrent laryngeal nerve. As most tumors are distal esophageal or gastroesophageal junction tumors, we do not perform aggressive nodal dissection near the thoracic inlet, which decreases the chance of recurrent nerve injury. The vagi are divided at the level of the azygos vein to minimize traction injury. It is important to avoid thermal injury to the airway and the pericardium during thoracoscopic mobilization of the esophagus. If the anastomosis is in the neck, we preserve the mediastinal pleura above the azygos vein. This may help to maintain the gastric tube in a mediastinal location; it could also help to seal the tissue around the gastric tube near the thoracic inlet, thereby minimizing the downward extension of a cervical leak, should it occur, into the chest.

The distal esophagus and the gastric conduit are brought into the chest with care taken not to twist the conduit. We prefer a high intrathoracic anastomosis near the thoracic inlet; however, one should not divide the esophagus too proximal which makes construction of the intrathoracic anastomosis technically difficult. When there is a concern with the proximal extent of the tumor, re-endoscopy may be required, at this point to determine the site of transection. The port at the 8th space posteriorly is enlarged, and protected with a wound protector; the specimen is removed and sent for frozen section analysis of margins.

Construction of anastomosis

We perform a stapled intrathoracic anastomosis. The first step is placement of a 28 mm EEA anvil in the proximal esophagus, which is secured with purse-string suture. It is difficult to place this first suture perfectly, as the anvil tends

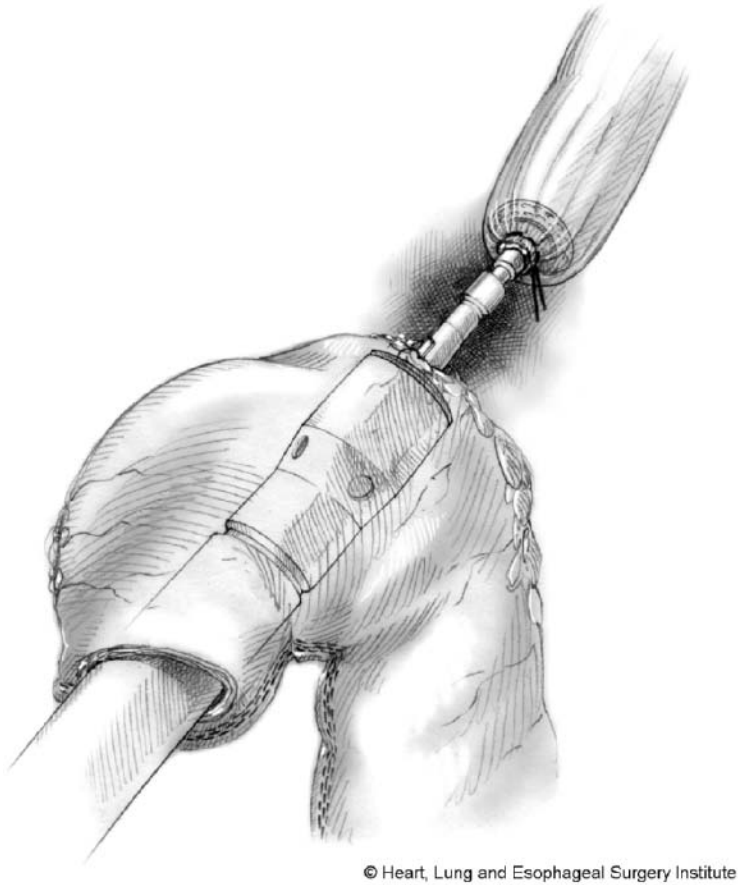

Figure 11.4 Diagrammatic representation of the construction of EEA anastomosis.

to move and migrate out of the open esophagus. Therefore, we always add a second purse-string suture to secure the anvil. Since the fundus of the stomach is the most ischemic portion of the conduit, we plan to discard the fundal tip. The fundus is then opened; the EEA stapler is then advanced into this gastrotomy. We then perform a stapled anastomosis between the gastric conduit and the esophagus, high above the azygos vein (Figure 11.4). The redundant portion of the fundus is then excised with a reticulating endo GIA stapler (Figure 11.5). A nasogastric tube is placed across the anastomosis under direct visualization and secured.

The avoidance of using the tip of the fundus, which is the most ischemic area, helps minimize the leaks. In an effort to further decrease leaks, we have recently adopted the technique of buttressing the anastomosis with an omental flap. It is important to drain the chest well and place drains strategically

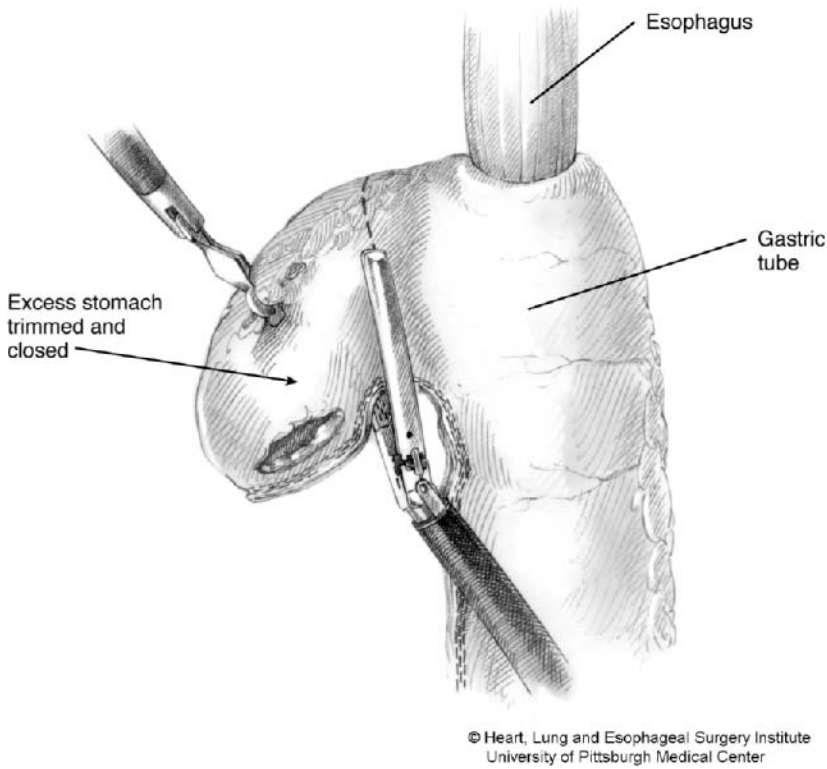

Figure 11.5 The redundant and excess fundus is excised with an endo GIA stapler.

in the chest since a well-drained leak should it occur, is easy to manage. We place a 28-French chest tube posteriorly in the pleural space, and a second #10 Jackson–Pratt drain posterior to the anastomosis, tracking behind the gastric conduit to the diaphragm, exiting at the costophrenic angle. It is also important to secure these drains well. If the anastomosis is performed in the neck, a similar stapled technique or a hand-sewn anastomosis can be constructed.

Complications

In general when complications occur, a low threshold for an open approach or conversion to an open approach is advised, particularly early in the surgeon's experience.

Recurrent nerve injury vocal cord palsy

Incidence

Recurrent laryngeal nerve (RLN) palsy has been reported in 4–20% of patients [10] with most larger series reporting a range of 4–7%. In our series of 222

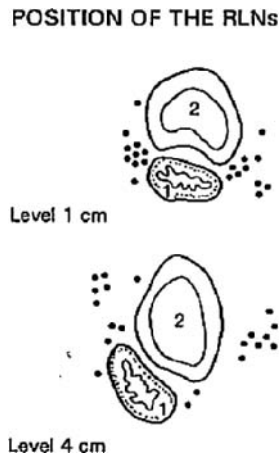

Figure 11.6 Position of the recurrent laryngeal nerve (RLN) in relation to the trachea and esophagus at a level 1 and 4 cm inferior to the cricoid cartilage in the transverse sections of 10 specimens. Note the increased distance of the RLN from the esophagus at a lower level. (*Source*: Reproduced with permission from the Annals of Thoracic Surgery [14]).

consecutive MIEs with a cervical anastomosis, RLN occurred in 3.6% of patients [3]. In a metaanalysis of more than 5000 patients, comparing transhiatal to transthoracic esophagectomy, the risk of RLN injury was 11% with a transhiatal approach, and 4.2% with an Ivor–Lewis approach [11]. Hulscher in another metaanalysis showed a relative risk reduction of 0.36 with a transthoracic approach [12]. The consequences of RLN injury can be serious. Patients not only are hoarse, RLN injury may also affect swallowing and the ability to generate a good cough and protect the airway, leading to an increase in pulmonary complications. Not surprisingly, Hulscher reported a 10-fold increase of pulmonary complications from 2.4% to 24% [13]. It is clear that prevention of RLN is an important consideration in esophageal surgery.

Prevention

Anatomy

In order to prevent recurrent nerve injury it is important to understand the anatomy which has been described by Liebermann-Meffert and colleagues [14]. The RLNs arise from the vagus nerve and on the left side, it loops around the ligamentum arteriosum and on the right it loops around the subclavian artery. They then ascend into the neck, with the left being longer (13 cm) compared to the right (7 cm). Importantly, both the RLNs are further away from the trachea and the esophagus caudally and become closer to the larynx superiorly (Figure 11.6). About 2–3 cm prior to entering the larynx, the RLN is closely associated with the inferior thyroid artery, where it traverses either anterior, posterior, or in between the vessel's branches. Each nerve enters the larynx posterior to the inferior cornu of the thyroid cartilage. Although, experienced surgeons may avoid injury to the RLN by avoiding its course, it may be prudent to identify the nerve during the dissection to avoid injury.

Some of the factors which may help avoid injuries in the neck include: (i) use of magnification loops to aid in the dissection. (ii) When a cervical esophageal

anastomosis is performed, the site chosen for anastomosis as long as oncologically sound, should be as low as possible, since the nerve is farther from the esophagus (Figure 11.6). (iii) It is important to keep the dissection plane on the esophagus itself. In particular, when a clamp is used to encircle the esophagus, it is important to stay on the esophageal muscle itself, so that the nerve on the opposite side is not injured. (iv) Self-retaining retractors should not be used in the neck; finger retraction deeper in the neck prevents RLN injuries. (v) Finally, prevent injury to the inferior thyroid artery. If there is bleeding it is important to judiciously control this vessel and avoid injury to the RLN which is closely associated with it [14, 15].

Similarly the RLN is at risk for injury in the chest, although the incidence is lower. Although, our incidence of RLN with an Ivor–Lewis approach is very low, both RLNs are at risk even with a right-sided thoracic approach. The left nerve is at risk as it courses behind the aortic arch. The right RLN can be injured during esophageal mobilization, where the nerve is particularly vulnerable near the thoracic inlet and close to the subclavian artery. Early division of the vagus may help with prevention of traction injuries as the esophagus is being mobilized. In addition, with gastroesophageal junction tumors we avoid dissection of very high mediastinal lymph nodes above the level of the azygos to avoid injury to the nerve.

Diagnosis and treatment

Wright and colleagues have provided a detailed review of options for vocal cord paralysis [15]. Most vocal cord palsies are temporary with a gradual return of laryngeal function over a period of several weeks. The manifestations of vocal cord paralysis include (i) change in voice (hoarseness and dysphonia) and this is best assessed by laryngeal stroboscopy, (ii) difficulties in swallowing are more morbid compared to changes in voice, and patients who are most susceptible to swallowing dysfunction are older and have decreased pharyngo-laryngeal sensation. This decrease in sensation is aggravated by the decline in motor and sensory function of the glottis, associated with RLN injury, predisposing these patients to aspiration. Evaluation includes assessment by a speech pathologist and consultation with an otolaryngologist. Phonosurgical procedures enhance glottis closure. Strategies to enhance pharyngo-laryngeal sensation include altering the temperature and the consistency of the food of the patient. (iii) Some patients present with stridor and dyspnea after extubation. This may even be present after unilateral RLN injury and urgent consultation with an otolaryngologist is recommended.

The treatment of laryngeal dysfunction associated with vocal cord paresis is individualized. The surgical treatment can be classified into transoral injection medialization or laryngoplastic phonosurgical reconstruction [15]. In general we favor consideration for vocal cord injection. This helps the patient generate an adequate cough, with pulmonary toilet, and potentially decreases pulmonary complications.

Anastomotic leaks and gastric tube necrosis

Incidence

Anastomotic leak is one of the most serious complications after esophagectomy. The rate of leak reported in the literature varies widely [10, 16–18]. There are several factors which have been implicated [19, 20]. These include the conduit used, the location of the anastomosis, the technique of anastomosis, nutritional status of the patient, the use of neoadjuvant therapy, and ischemia of the conduit. In a study by Briel, the leak rate was higher with a gastric conduit in the cervical location when compared to colonic interposition [21]. Orringer reported a leak rate of 13% in a series of 1085 patients who underwent transhiatal esophagectomy [17]. In a newer modification of the anastomosis, he reported a decreased leak rate of 2.7% [18]. The location of the anastomosis may make an impact on the leak rate. Some reports show a lower leak rate of intrathoracic esophago-gastric anastomosis compared to the cervical anastomosis, but this has not been proven by randomized studies [22]. In our experience with MIE and a cervical anastomosis, the leak rate was 11.7%, and was 6% when a broader gastric tube was used. In our initial experience with minimally invasive Ivor–Lewis approach, the leak rate was 6%. In a randomized study by Walther and associates comparing a cervical anastomosis with an intrathoracic anastomosis, no differences in leak rate were demonstrated [22]. There are several studies which have compared hand sewn to stapled anastomosis. They suggest that comparable results can be obtained by both techniques, and the preference of the anastomotic technique depends on the expertise of the surgeon [16].

Prevention

The principles of prevention of an anastomotic leak after MIE are similar to the open technique. Ischemia of the gastric conduit is one of the primary reasons for anastomotic leaks. Mobilization of the stomach should be done with utmost care and gentle handling. During mobilization, it is critical to preserve the gastroepiploic arcade, and preserve not only the arterial supply but also the venous drainage. Full mobilization of the stomach requires careful division of the posterior attachments of the stomach, attachments to the colon, and a Kocher maneuver.

The size of the gastric tube is important in avoidance of a leak. Lieberman-Meffert and colleagues in an elegant study showed that that 60% of the primary blood supply for the gastric tube comes from the right gastroepiploic artery, 20% from the collaterals via the left gastroepiploic artery, and the fundal tip (20%) is supplied via collaterals from the mucosal and submucosal collaterals [23]. Although we attempt to preserve the right gastric artery, Lieberman-Meffert showed that the contribution of the right gastric artery is minimal and it can be divided if needed to help with complete mobilization of the gastric conduit. They also reported that the ideal width of the gastric tube is 4–5 cm in diameter. We have found that a very narrow gastric tube had a

high leak rate, and this can be substantially lowered with a broader 4–6 gastric tube [3].

In addition to the above factors, our approach to prevention of these leaks includes avoidance of twisting of the gastric conduit as it is delivered to the chest or the neck, avoidance of constriction of the conduit at the hiatus, avoidance of distension of the conduit, meticulously performed anastomosis, and locating the anastomosis in the chest. Further, we discard the tip of the fundus, which is the most ischemic area of the conduit during the construction of the anastomosis with a 28 mm EEA stapler (Figure 11.5). In addition, more recently we have added an omental patch, to buttress the anastomosis to reduce the incidence of leak, particularly in patients who may be at higher risk (e.g., after chemo-radiation). At the conclusion of the laparoscopic phase, we tack the stomach to the hiatus with interrupted sutures. It is important during this step not to compromise the vascular supply of the stomach and avoid too much constriction of the conduit by the hiatus. In addition, it is important to strategically place drains in the chest, to drain the leak in case this occurs. It is far easier to manage a well-drained leak than one which is not controlled.

Diagnosis and management

The spectrum of presentation of leaks range from early fulminant (within 48 hours) which is typically caused by gastric conduit necrosis to clinically asymptomatic leaks. Urschel provided a useful classification of leaks ranging from clinically symptomatic leaks, clinically apparent cervical leaks, clinically apparent thoracic leaks, and early fulminant leaks [24]. The diagnosis of esophageal leak is confirmed with a contrast study.

If a leak is identified, appropriate therapy is instituted, depending both on the location and severity of the leak. It is important to assess the status of the gastric conduit by esophagoscopy to rule out any ischemia early in the evaluation. The degree and extent of proximal gastric ischemia or necrosis and the clinical status of the patient will also dictate the further management in these patients.

Cervical leaks

Most isolated cervical anastomotic leaks can be treated conservatively by opening the neck incision and creating a controlled fistula [25]. Patients with a small area of proximal necrosis, who have established good fistulous drainage and are clinically stable, may be carefully observed. In some patients with cervical leaks, the areas of necrosis can be debrided and the wound left open, with daily dressing changes. Early endoscopy and dilation may also be useful in minimizing strictures. In some despite the leak in the neck, there may be extension into the mediastinum and this should be drained either by an operative approach with chest/mediastinal exploration or percutaneous computed tomography (CT)-guided drainage.

Intrathoracic leaks

The principles of management of patients with an intrathoracic leak again depend upon the severity and the clinical status of the patients. Endoscopy is again essential to assess the status of the gastric conduit. Small contained leaks can be managed conservatively. It is important to drain the leak well, and drains well placed in the operating room are helpful should a leak occur. Any undrained leak or fluid collection should be drained operatively or with CT guidance. In the absence of significant ischemia of the gastric conduit, a contained leak or a well-drained leak typically heals. In some patients, operative repair with a buttress may be required. The role of stents in the management of leaks is not well defined [26].

Gastric tube necrosis

At the other end of the spectrum are patients with early fulminant presentation due to gastric conduit necrosis [27]. Gastric necrosis is one of the most serious complications of esophagectomy and occurs in less than 3% of cases. In our series, the incidence was low, but was associated with the use of a narrow conduit [3].

The patient should be rapidly resuscitated, and taken to the operating room with broad spectrum antibiotic coverage. Intraoperative decisions are based on the surgeon's judgment at the time of endoscopy and the patient's clinical status. With gastric conduit necrosis, the nonviable conduit is resected and the ischemic but viable remnant should be brought back to the abdomen. A cervical esophagostomy is performed for complete diversion, maintaining as much length of the cervical esophagus as possible. A second look operation may be necessary to assess the ischemic stomach if part is left behind. A tube can be placed in the gastric remnant, for drainage in the early postoperative period, and feeding later on. A jejunostomy feeding tube if not already performed, should be placed for enteral nutritional support. The chest and mediastinum are debrided, with meticulous and wide drainage. After a period of recovery, rehabilitation, and nutritional optimization, the patient can undergo delayed reconstruction using a colon interposition [10]. In some cases, bolus feedings through the gastrostomy tube will provide sufficient dilation to allow the stomach to be reused as a conduit.

Finally, patients who develop a leak are more likely to develop an anastomotic stricture. Early initiation of endoscopic dilation is useful in decreasing the severity of the stricture and its treatment. It is important to exclude recurrent disease in patients who develop a late stricture.

Diaphragmatic hernia

Incidence

Diaphragmatic hernia through the hiatus is an uncommon complication following esophagectomy. In our experience, this complication occurred in less

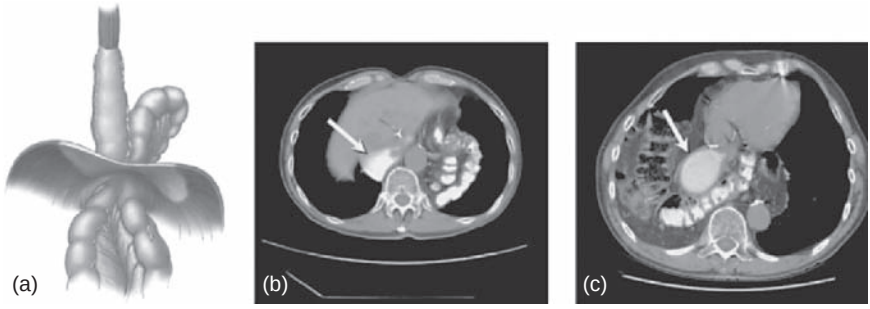

Figure 11.7 Diaphragmatic hernia. (a) Diagrammatic representation of the hiatal hernia. (b) Herniation between the greater curve of the stomach filled with contrast (arrow) and the left crus. Transverse colon has herniated into the left chest. (c) Herniation posterior to the gastric conduit (arrow), with colon in the right chest. (*Source*: Reproduced with permission from the Annals of Thoracic Surgery [28]).

than 3% after MIE [28]. The incidence may be higher following the laparoscopic approach due to lack of adhesions. The contents of the hernia typically consist of large or small bowel and occurred predominantly on the left side (Figure 11.7).

Prevention

During the laparoscopic portion of the esophagectomy, care should be taken to assess the hiatus, and the decision to enlarge the hiatus should be individualized. We usually divide the crura to accommodate the gastric conduit. When there is a large pre-existing hiatal hernia, no division of the crura is required. If a McKeown type MIE is performed, after construction of the anastomosis in the neck, traction is gently applied to the distal stomach to reduce any redundant conduit back in the abdomen, and tacking sutures are placed between the stomach and the crura. These sutures are placed between the left crura and the greater curvature, with care being taken not to compromise the gastroepiploic vessels, between the conduit and the diaphragm anteriorly and between the lesser curve of the conduit and the right crura. When an Ivor–Lewis MIE is performed, these sutures are placed between the gastric conduit and the crura from the chest. It is important to calibrate the hiatus so as not to allow herniation, and at the same time avoid narrowing and obstruction of the conduit.

Treatment

Treatment consists of reduction of the hernia contents with an open or laparoscopic approach. As with other complications, a low threshold for an open approach or conversion to an open approach is advised when dealing with complications. The principles of repair include reduction of the hernia, complete mobilization of the crura posterior to the conduit to allow a tension-free repair of the crura. It is important to preserve the peritoneal lining of the crura to preserve their integrity. In some instances, a relaxing incision in the

diaphragm to approximate the crura without tension or reinforcement with a mesh may be required.

Redundant gastric conduit

Incidence and prevention

The incidence of redundant gastric conduit after MIE in our experience was 3.6% [28]. Prevention of this complication should take into factors which are potentially responsible for this complication which include excess conduit left behind in the chest at time of the esophagectomy, mechanical obstruction of the conduit leading to dilation and redundancy, and a twisted gastric conduit. The sites of obstruction may lie at the level of the pylorus, or at the level of the hiatus (Figure 11.8). In our analysis, the cause of a redundant conduit was mechanical obstruction in a majority of patients.

Treatment

We offer revisional surgery for patients with symptoms. As with other redo surgery after esophagectomy, it is important to exclude recurrence prior to surgical correction. The ideal approach is a sequential thoracic and abdominal approach. Through a right transthoracic approach, the conduit is completely

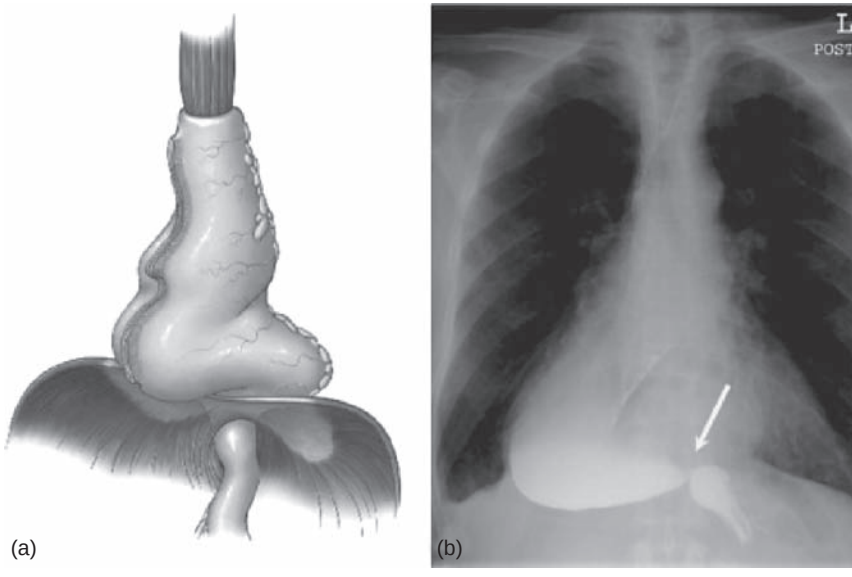

Figure 11.8 Redundant conduit. (a) Diagrammatic representation of redundant conduit. The horizontal portion of the conduit above the diaphragm impairs gastric emptying. (b) Barium swallow of a redundant conduit. Several causes may lead to this end-stage appearance (see text). Gastric outlet obstruction due to the lack of a pyloric drainage procedure was the reason for obstruction in this patient (arrow). (*Source*: Reproduced with permission from the Annals of Thoracic Surgery [28]).

mobilized in the chest, and mediastinal adhesions lysed. It is important to avoid injury to the gastroepiploic vessels during this mobilization. If the conduit is twisted, this is corrected. Where the gastric conduit is excessively dilated, a narrower 5–6 cm gastric tube can be created. The excess conduit is then transferred into the abdomen through an abdominal approach (midline abdominal incision). If mechanical obstruction is noted at the level of the pylorus, a pyloroplasty or pyloromyotomy can be added to the procedure. Similarly, if the level of obstruction is at the level of the hiatus, this is corrected at the time of surgery. As described earlier, the hiatus is calibrated; the stomach is tacked to the diaphragm to prevent future herniation.

Chylothorax

Incidence and diagnosis

Chylothorax has been reported in 1–5% of patients following esophagectomy [10,29]. In our series of minimally invasive esophagectomies, the incidence of chylothorax was 3% [3]. Chylothorax is a potentially serious complication which can lead to malnutrition, immunocompromise, and sepsis with a significant morbidity and mortality.

Chylothorax is defined as lymphatic fluid enriched with chylomicrons and fat which leaks into the pleural space [30, 31]. The primary causes for a chylothorax is a leak from the main thoracic duct or less commonly, a leak from a lymphatic branch of the main duct. The diagnosis is typically made by the characteristic milky appearance of the pleural fluid and is confirmed by analysis of the fluid showing increase in triglycerides or a positive Sudan fat stain [30,32,33].

Prevention

During the thoracic part of dissection, we routinely apply clips generously when mobilizing the esophagus particularly along the posterior aspect, to control any lymphatic ductules branching from the main duct. Although we do not routinely ligate the thoracic duct, if an injury to the thoracic duct is recognized, the main duct is ligated. Some authors have advocated administering cream prior to the esophagectomy to aid in the identification of the thoracic duct intraoperatively, and either protect or ligate the duct [34]. In this study, in addition, if any leak from the divided accessory ducts was noted, these were also ligated. Using this technique, Shackcloth and colleagues reported that their rate of chylothorax decreased from 7.5% (12/158) to 0% (0/93) [34]. In our experience, the majority of chylothoraces occurred early in the learning curve phase of this procedure and can be prevented by careful technique.

Treatment

Once the diagnosis of chylothorax is confirmed, it is reasonable to attempt conservative treatment. The patient is kept on NPO, placed on medium chain triglycerides or total parenteral nutrition, and the chest tube output is

monitored. It is critical to drain the pleural space well with thoracostomy tube/s so that the lung is completely expanded. In some patients, both pleural spaces need to be drained. When conservative management is not effective, surgery is indicated.

Prior to surgery, it is prudent to obtain a barium swallow, to rule out an anastomotic leak which can be managed at the same time. Some advocate lymphangiography [35] to delineate the site of the chyle leak. Fat should be administered via the jejunostomy tube prior to the operation, and this will aid in identification. The approach is through a right thoracoscopy or thoracotomy. The conduit is retracted carefully and the site of the leak is identified. The site of the leak is most commonly from the main thoracic duct and this is ligated. If the leak is from the branches of the thoracic duct, these can be controlled with clips. If the leak is from a lymph node basin where a lymphadenectomy was performed, application of fibrin glue may be useful [36]. Finally, a mechanical pleurodesis and thoracostomy tubes to drain the pleural space complete the procedure.

Airway injuries

Incidence

Injury to the airways is an infrequent complication of esophagectomy and has been reported to be less than 2% in the literature [17,37]. In our experience, the incidence is about 1% [3].

Prevention

Airway injuries usually occur along the membranous portion of the trachea or mainstem bronchi due to blunt traction or thermal injury during thoracic esophageal mobilization. During dissection, it is important to identify the tracheal bifurcation and the mainstem bronchi during the esophageal mobilization. One has to use the ultrasonic coagulating instrument carefully around this area to prevent thermal injuries to the airway. Early in one's experience with MIE, it is prudent to perform the esophagectomy in an open fashion rather than with a thoracoscopic approach for bulky mid-esophageal tumors, particularly after neoadjuvant therapy, to avoid this complication.

Treatment

Injury to the airway is identified intraoperatively, by direct observation and by an air leak. A primary repair can be accomplished in these patients. The endotracheal tube should be carefully advanced, if possible, beyond the site of injury. It is important to avoid extension of the injury by this maneuver, and advancement of the endotracheal tube with bronchoscopic guidance is advisable. The injury is repaired primarily in the acute setting. When the injury presents later, we recommend a thoracotomy, takedown and repair of the fistula, with a buttress (intercostal muscle, serratus, lattissmus dorsi muscle, pleural flap, or omentum).

Conclusion

Esophagectomy is a complex procedure, and the performance of a MIE further increases the complexity of this operation. Factors associated with improved outcomes include hospital volume and the volume and training of the surgeon. Important aspects of avoiding complications include the experience of the surgeon, careful patient selection, meticulous operative technique, and attention to detail in postoperative care.

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CHAPTER 12

Operations for Benign Esophageal Disorders

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Introduction

There exist many benign disorders of the esophagus that can be managed via surgical intervention. The most common of these include gastroesophageal reflux disease, paraesophageal hiatal hernia, and achalasia. Although the signs, symptoms, operative indications, and approaches may differ for these disorders, they do share many of the same concerns with regard to perioperative care. For all these disorders, minimizing the operative morbidity and optimizing outcome require attention to detail with regard to preoperative testing, patient selection, preoperative preparation, choice of operative incision, and postoperative care.

Preoperative testing

The most important step in avoiding operative complications may be ensuring one has made an accurate diagnosis. There is a core of "standard" tests that are commonly obtained in patients suspected to have esophageal disorders. These generally fall into one of two categories: imaging tests such as endoscopic visualization and radiographs, and those that assess esophageal physiology and function. Both types of tests can be clinically important when determining operative candidacy and selecting appropriate surgical procedures.

In the past, the contrast esophagogram (most often a barium swallow) was the most important single test that could be obtained. It provided structural and anatomic information (size and shape of esophagus, presence of gastric herniation, stricture, diverticulum, etc.), as well as a modicum of physiologic information (presence of peristalsis, rate of esophageal emptying, and spontaneous reflux). While this test is still frequently obtained, flexible esophagogastroduodenoscopy (EGD) has supplanted a contrast study as a single most

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critical test to be ordered initially. The EGD not only provides the attentive observer the same structural information as the contrast esophagogram but also allows for the visualization and identification of specific mucosal abnormalities (esophagitis, Barrett's mucosa) that cannot be easily appreciated radiographically. Additionally, it provides the opportunity for diagnostic biopsy of mucosal lesions, which may also assist the practitioner in decision making. No patient should be subjected to esophageal surgery without first having undergone a thorough flexible EGD, preferably by the surgeon planning to undertake the operation or a practitioner he/she knows or trusts.

Physiologic testing can be crucial in the operative decision making process. A 24-hour esophageal pH test remains the gold standard for diagnosing pathologic gastroesophageal reflux disease (GERD). Many of the signs and symptoms of esophageal disorders such as dyspepsia, substernal epigastric discomfort, belching, and bloating can occur with a variety of abdominal disorders including primary disorders of the pancreas, gallbladder, stomach, and intestines. In patients with primarily such nonspecific symptomatology, a 24-hour pH test can be vital to the determination of whether or not a patient is an appropriate candidate for reflux surgery. While it may be not be absolutely necessary in a patient with a classical presentation of GERD (substernal burning, water brash, presence of hiatal hernia, presence of esophagitis, and initial response to antisecretory medication), for those patients who do not present with classic signs and symptoms, a 24-hour pH test can prevent an incorrect diagnosis that otherwise might result in the performance of an inappropriate surgical procedure.

Esophageal manometry is perhaps the single most important physiologic test that one can perform in a patient with esophageal symptomatology and is indicated in virtually all patients being considered for functional esophageal surgery. This is a simple, quick, and relatively noninvasive test that is a gold standard for diagnosis in patients with achalasia, some of whom will complain of reflux-like symptoms early in the course of their disease. Undertaking manometry in such patients with early achalasia who have minimal obstructive symptoms can prevent an incorrect diagnosis of GERD that might otherwise lead to a fundoplication with resultant severe dysphagia.

Those patients with either GERD or a giant paraesophageal hiatal hernia should also be considered for manometry prior to surgical intervention. It is important to recognize grossly inadequate esophageal motility in the form of profoundly low amplitude contractions or nonperistaltic muscular activity such as one sees in scleroderma, a disorder that often results in GERD. If one fails to appreciate such abnormal motility and then proceeds to a complete fundoplication, it is quite likely to result in severe and persistent postoperative dysphagia. Not infrequently this could result in the need for a second operation to relieve the obstruction.

Two additional physiologic tests may occasionally be called for in the workup of benign esophageal disorders. A gastric emptying scan may alert the surgeon to the presence of profound gastroparesis, a condition that may

predispose to failure of fundoplication due to persistent symptoms. While it would be inappropriate to perform this test routinely, the presence of undigested food in the esophagus or in the stomach during flexible EGD despite an appropriate fasting history should lead the physician to investigate gastric emptying.

Nuclear esophageal emptying scans may also occasionally be helpful when dealing with complex motility disorders but in general are not necessary for decision making in the majority of patients with benign esophageal disorders.

Patient selection

Once the correct diagnosis has been established, one must decide whether or not the patient is an appropriate candidate for surgical intervention. Clinical assessment of functional and cardiopulmonary reserve is appropriate for all patients; those who are elderly, frail, or who have a history of atherosclerotic disease may require formal evaluation via stress tests and/or pulmonary function testing. Many elderly patients with giant paraesophageal hernias have very limited respiratory and/or cardiac reserve and thus have an exceedingly poor functional status. In such patients, avoidance of a major operation is likely the best course for the patient unless they present with serious symptoms of obstruction such as postprandial chest pain, retching, and weight loss. Fragile patients with mild symptomatology are often best managed medically.

Similarly, morbidly obese patients with benign esophageal conditions do not necessarily require operative intervention. In most of such patients, it is perfectly appropriate to undertake an aggressive medically monitored program of exercise and nutrition to achieve significant weight loss prior to surgical intervention. For patients such as those with esophageal reflux, such a weight loss can ameliorate the symptomatology and even obviate the need for surgical intervention. Performance of an antireflux procedure in obese patients has been reported to increase risk of long-term failure. For the subset of patients who are truly morbidly obese (BMI greater than 40) and who are unable to achieve significant weight loss, an antireflux procedure may be less beneficial to the patient than a targeted bariatric procedure that will often achieve both a significant weight loss and relief of reflux symptomatology.

Preoperative preparation

Antibiotic coverage

Prophylactic antibiotics are indicated routinely for esophageal surgery. For the majority of uncomplicated procedures such as fundoplication or myotomy, a simple first-generation cephalosporin administered as one dose at least 1 hour prior to surgery is all that is necessary. More aggressive prophylactic antibiotic regimens for coverage of Gram-negative and anaerobic organisms may be appropriate if one anticipates a high risk of perforation into viscus such as in those patients with multiple prior esophageal procedures.

Prophylaxis for deep venous thrombosis

Prophylaxis for deep venous thrombosis is appropriate for virtually all patients undergoing esophageal surgery. This is particularly true for those patients undergoing laparoscopic procedures in which a dorsal lithotomy position will be utilized often in conjunction with reverse Trendelenburg positioning. Such positioning tends to lead to a venous stasis in the legs, and thus utilization of sequential compression stockings as well as daily subcutaneous heparin or Lovenox is warranted.

General health considerations

Patients who smoke should ideally stop smoking for several weeks prior to surgery. As noted above, morbidly obese patients should be encouraged to lose weight. Conversely, patients with severe weight loss due to obstructive symptoms should be assessed. In severe cases of malnutrition, preoperative preparation with intravenous or enteral tube feedings should be considered. Finally, patients with achalasia or other obstructive lesions should be limited to clear liquids for 24–48 hours prior to surgery to minimize the risk of aspiration at the time of induction.

Surgical approach

Most esophageal surgeries can be performed either through a thoracotomy, a laparotomy, a thoracoabdominal, or a laparoscopic approach. Because of its minimally invasive nature, laparoscopy is rapidly becoming the approach of choice for most benign esophageal surgery. It has been demonstrated to be less invasive and allow for shorter hospital stays and with a quicker return to activities of daily living. However, the open approach is via the chest and/or abdomen continues to be advantageous in specific situations.

For those patients who have undergone multiple open abdominal procedures, laparoscopy can prove to be a quite difficult proposition due to extensive adhesions. In such patients, an approach to the esophagus via a "virgin" left chest may result in a shorter and easier operation with less risk of inadvertent esophageal/gastric perforation and/or damage to surrounding organs. This approach also allows for optimal esophageal mobilization. Finally, the thoracic approach may be especially appropriate for patients who are morbidly obese (BMI greater than 35) as well as those patients in whom there is concomitant intrathoracic pathology that must be addressed.

The combined thoracoabdominal approach with partial circumferential diaphragmatic incision provides unparalleled exposure of all key anatomy above and below the hiatus. However, it is also a painful incision that may limit postoperative pulmonary toilet and mobilization. For this reason, it is usually reserved for the setting when multiple prior esophageal procedures have been performed, thus increasing the difficulty of perihiatal dissection. When either a thoracotomy or thoracoabdominal approach is contemplated, placement of a thoracic epidural catheter for pain management should be

considered in order to optimize pulmonary toilet and prevent respiratory complications.

Postoperative management

Most patients undergoing benign esophageal procedures will be candidates for immediate extubation in the operating room and early postoperative mobilization. The intraoperative and the postoperative administration of intravenous ketorolac and odansetron help in the management of immediate postoperative pain and nausea.

Very few will require indwelling nasogastric tubes. Such tubes tend to inhibit the pulmonary toilet and the incidence of true ileus postoperatively is relatively small. Pain management is an important component of postoperative care that facilitates early mobilization and pulmonary toilet, both of which are helpful in the prevention of pulmonary complications. The optimal strategy depends on the operative approach. Patients undergoing laparoscopy can usually be managed with IV ketorolac, one or two intravenous doses of opiates as necessary, and oral codeine or hydrocodone compounds once oral intake resumes on the first postoperative day. Early removal of a urinary catheter allows for same day immobilization, which minimizes the risk of deep venous thrombosis and respiratory problems.

Patients with open incisions are optimally managed with epidural catheters using a combination of opiates and long-acting local analgesic agents for the first 3–4 days following surgery. In such cases, bladder catheters should be maintained until the epidural catheter is removed.

Routine postoperative imaging was performed early in the laparoscopic experience but is no longer indicated in uncomplicated cases. A contrast swallow is used postoperatively in a selective fashion, specifically in those patients in whom there is a recognized intraoperative perforation or those with unexplained postoperative fever or leucocytosis. Such patients undergo a gastrographin swallow followed by dilute barium to rule out a leak prior to the resumption of oral intake. Otherwise, a routine barium swallow following benign esophageal surgery usually offers little useful information and it rarely alters management.

Operative maneuvers

Surgery for GERD

It has been suggested that up to half of the clinical failures following fundoplication may be due to intraoperative technical errors. Whether the operation is done via an open abdominal, open thoracic, or a laparoscopic approach, there are several operative maneuvers that must be undertaken appropriately in order to maximize the chance for clinical success.

The first of these is careful and adequate dissection of the hiatus and esophagus. Mobilization of the esophagus requires division of the phrenoesophageal

membrane and care should be taken to begin this dissection immediately adjacent to the crural pillars where a plane of dissection is easier to find. Trying to dissect blindly through the middle of parahiatal fat may result in bleeding and inadvertent damage to surrounding structures. Ideally, the peritoneum as well as the endoabdominal and endothoracic fascia should be preserved on the crural pillars to avoid a hiatal closure composed of denuded crural muscle fibers. Most patients with GERD will have a hiatal hernia and adequate circumferential intrathoracic dissection of the esophagus should be undertaken for a distance of 5 cm proximal to the GE junction. The goal is to have 2–4 cm of esophagus lie loosely within the abdomen without tension. Care should be taken to avoid damage to the vagal nerves to minimize the chance of postoperative gas bloat syndrome. The gastrophrenic and gastrosplenic ligaments should be divided as well. This allows for a generous retroesophageal window, which will allow an easy tension-free passage of the back wall of the fundus along the posterior aspect of the esophagus. The "shoeshine" maneuver can be performed intraoperatively, which demonstrates an adequate retroesophageal space.

Occasionally in patients with giant paraesophageal hiatal hernia or severe chronic esophagitis (such as those with Barrett's), there will be a great deal of periesophageal inflammation and fibrosis. In such patients, the esophagus can be foreshortened and it may not be possible to deliver 2 cm or more of esophagus into the abdomen in a tension-free fashion. It is inappropriate to attempt the construction of a subdiaphragmatic wrap under tension. Such a wrap has a high likelihood of failure either due to intrathoracic migration of the wrap or due to distal slippage of the wrap into the body of the stomach with a resultant gastrogastric wrap (the so-called "slipped" Nissen). These problems can occur acutely in the postoperative period or may present months to years after the initial procedure. Presenting symptoms often include chest pain, dysphagia, and recurrent reflux symptomatology.

In such patients, a lengthening procedure is indicated. While there are currently at least three different techniques for esophageal lengthening (see Figure 12.1), the most common one currently performed via laparoscopic approach is the wedge gastroplasty. This maneuver is begun by passing a 50–56 French dilator into the esophagus and situating it along the lesser curve of the stomach. A wedge-shaped portion of the fundus immediately adjacent to the cardia is then resected creating a 2–3-cm-long "neoesophagus" from the lesser curve. This newly created esophagus lays tension-free within the abdomen and allows the appropriate site for performance of a fundoplication.

Occasionally, during the periesophageal and/or gastric dissection, a full-thickness perforation may occur and immediate repair should be undertaken, usually with single-layer closure. When this occurs in the distal esophagus, the subsequent performance of a fundoplication will serve to buttress the closure. If such a perforation occurs at a site where such a gastric buttress is not available, one can consider utilization of omentum to reinforce the closure. In such patients, a nasogastric tube is usually left in place until a postoperative

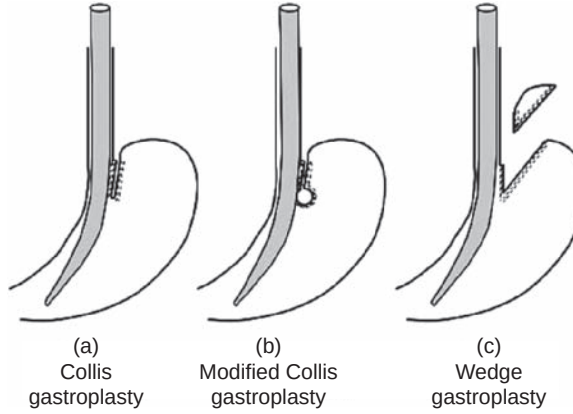

Figure 12.1 Surgical options for lengthening a foreshortened esophagus by creation of a neoesophagus utilizing an indwelling dilator as a "sizer." (a) Classic stapled Collis gastroplasty; (b) modified stapled Collis gastroplasty; (c) wedge gastroplasty.

contrast swallow (usually performed on the following day) confirms the absence of a leak. The NG tube is then removed and oral intake begun. If a contained leak is observed and the patient appears well (normal pulse, temperature, respiratory rate, WBC, etc.), conservative management with nasogastric drainage, broad-spectrum antibiotics, and parenteral alimentation is undertaken until the leak has sealed. A noncontained leak requires reoperation with drainage and suture closure of the leak, ideally with reinforcement using viable tissue (gastric fundus, omentum).

Accurate hiatal closure is another important maneuver in most procedures for benign esophageal disease. Although crural closure was not always performed early in the laparoscopic experience, a high incidence of posterior paraesophageal herniations was reported and crural closure is now routine. If the hiatal opening is excessively narrowed by sutures, postoperative dysphagia will result. Although crural closure can be performed by experienced surgeons without the need for dilator [1], for most practitioners, the insertion of an intraesophageal dilator (between 54 and 60 French in size) provides for a simple and reliable "sizer," which allows for the posterior crural sutures to be placed with the appropriate level of tightness. A prospective randomized trial demonstrated routine use of an intraluminal bougie did indeed result in a decreased incidence of long-term postoperative dysphagia [2].

The technique for crural closure has also been debated. If the crural pillars have not been skeletonized or damaged during dissection, a simple interrupted closure using nonabsorbable suture of size 0 can be utilized without the need for reinforcement with any form of mesh, buttress, or pledget. Although the routine utilization of a mesh has been reported, the short- and long-term complications of dysphagia and intraluminal erosion mitigate against the routine utilization of such a measure for routine hiatal hernia surgery [3, 4].

Perhaps the most controversial component of a fundoplication is the fundic mobilization via short gastric artery division. Many surgeons strongly believe this to be a critical component in the performance of a fundoplication in that it allows for a complete periesophageal wrap without any lateral tension; this is said to minimize the chance for postoperative dysphagia and/or breakdown of the wrap. However, this question remains open to debate and several randomized controlled trials suggest that there is no difference in short- or long-term success when short gastric vessels are left intact [5–7].

Finally, there has also been controversy regarding the type of wrap that is optimal for the management of a reflux. The most common procedure done is a full 360° wrap as initially described by Nissen. However, it has been suggested that a circumferential wrap can lead to an increased and unacceptable incidence of dysphagia and thus a noncircumferential 270° posterior wrap as described by Toupet has also been widely utilized. Although these are the two most frequently used methods, an anterior 180° wrap (Dor) has also been described.

Prospective randomized trials have suggested short-term equivalence of partial and complete fundoplication with regard to morbidity, mortality, and symptom relief [8–10]. Some clinicians believe that a partial fundoplication (Toupet, Dor) will result in less postoperative dysphagia but that the Nissen will provide a better long-term protection from recurrent reflux. At present, the Nissen appears to be the gold standard for most surgeons throughout the country; however, a Toupet can be very useful for patients with a profound esophageal dysmotility such as those patients with a scleroderma or patients with achalasia who have undergone a previous myotomy and have severe refractory reflux.

When performing a circumferential fundoplication, it is critical that the stitches incorporate a generous "bite" of the anterior wall of the fundus as well as the posterior wall. In addition, each of the sutures should include a generous "bite" of the esophagus; this latter maneuver tends to fix the wrap to the distal esophagus and minimizes the chance for distal migration that might result in a gastrogastric wrap ("slipped" Nissen) with return of symptoms.

Paraesophageal hiatal hernia repair

Most of the operative maneuvers noted in the preceding section dealing with fundoplication pertain as well to the repair of giant paraesophageal hiatal hernias. However, the marked anatomic disturbance found in giant hiatal hernias also creates some differences in optimal intraoperative technique. First and foremost is the management of the intrathoracic hernia sac. Dissection and removal of the sac from the chest is vital to minimize the chances for hernia recurrence. With an abdominal approach, the dissection is best undertaken in the plane outside the sac itself and the sac is delivered into the abdomen. Although actual resection of the sac following its delivery into the abdomen is not absolutely mandatory, many surgeons find that excising the sac allows for better identification of the gastroesophageal junction. Identifying the true

border between the stomach and the esophagus can be difficult in the giant paraesophageal hernias not only because of the sac, but also because of exuberant gastroesophageal fat pads that are often present. We prefer to excise both the sac and the fat pad taking great care to not to damage the adjacent left (anterior) vagus nerve. This allows for the accurate identification of the gastroesophageal junction, which is vital in the determination of whether or not a lengthening procedure will be necessary.

Another technical difference in the procedure in giant paraesophageal hernias is the difficulty of circumferential esophageal dissection. In patients with giant hernias, the esophagus forms the posterior wall of the hernia sac and must be dissected up off the aorta. Due to the chronicity of the hernia (usually decades), the esophagus may be fixed more firmly to the aorta than occurs in routine GERD patients. Periesophageal dissection may thus be more difficult but it is critical to perform this dissection as far proximal as possible in hopes of avoiding a lengthening procedure. Care must be taken not to damage the right (posterior) vagus nerve during this maneuver.

There is also a difference with regard to the technique of crural closure. For patients with giant paraesophageal hernias, the hiatus is grossly enlarged and there may be some attenuation of the crural pillars. This may make secure hiatal closure problematic and thus hernia recurrence is possible. The utilization of a prosthetic mesh has been reported to effectively decrease the incidence of recurrence; however, it also can lead to an increased incidence of postoperative dysphagia as well as episodic reports of intraluminal erosion and/or migration [3, 4, 11]. A recent prospective randomized trial reports the utilization of a bioabsorbable patch or buttress, which, when used to reinforce the crural closure, had significantly decreased the incidence of recurrence at 6 months [12]. The utilization of such a bioabsorbable buttress cannot currently be recommended definitively as a "best practice" due to a lack of a long-term follow-up and confirmatory studies. However, reinforcement of the crural closure with such a bioabsorbable product appears to be an attractive option and hopefully additional studies with long-term follow-up will allow determination of the value of such reinforcement.

Achalasia surgery

On the surface, achalasia surgery would appear to be diametrically opposed to gastroesophageal reflux surgery, for example, the intent is to destroy as opposed to strengthen the lower esophageal sphincter. However, many of the preparatory steps in the dissection of mobilization of the esophagus are similar. A careful dissection is necessary during the division of the phrenoesophageal membrane following which the left vagus nerve must be mobilized as it crosses the anterior surface of the lower esophageal sphincter. This latter maneuver allows for longitudinal division of esophageal musculature without inadvertent damage to the vagus nerve. Unlike with fundoplication, no division of short gastric, gastrosplenic or gastrophrenic ligaments is necessary.

In fact, maintaining these structures is likely beneficial and helps prevent intrathoracic gastric herniation as a result of the hiatal dissection.

It is important to perform full thickness division of both esophageal muscular layers over a distance sufficient to relieve the symptoms of dysphagia. This usually requires a myotomy 4–6 cm in length proximal to the gastroesophageal junction as well as identification with subsequent division of the gastric crural sling fibers. What constitutes an "adequate" myotomy has been a point of controversy for decades. Surgeons have proposed using several adjunctive maneuvers including intraoperative esophagoscopy [13] and real-time esophageal manometry [14] to determine the adequacy of myotomy. These may be helpful tools especially for surgeons early in their experience with the procedure. Although initially the gastric portion of the myotomy was described as 1–2 cm in length, extending this up to 3 cm onto the stomach has been suggested to maximize symptomatic benefit [15]. It is during this gastric musculature division that most inadvertent mucosal perforations occur. In the event of such a perforation, simple suture repair with 3-0 or 4-0 suture should be undertaken preferably without muscular closure. In such patients, the mucosal closure can be reinforced either with omentum or, if a partial fundoplication is to be performed, by undertaking an anterior 180° (Dor) fundoplication, which will allow coverage of the mucosal repair with the gastric wall. In such cases, barium swallow is routinely performed on the first or second postoperative day prior to the institution of oral intake.

A major controversy in achalasia surgery has been whether or not to perform a concomitant fundoplication to minimize the chances for gastroesophageal reflux. Although, the theoretical arguments against such a maneuver certainly exist, a recent randomized clinical trial demonstrated that the routine performance of a Dor (anterior 180°) fundoplication led to a decreased incidence of both symptomatic and asymptomatic reflux as documented by 24-hour pH testing and symptom questionnaires [16]. There was no corresponding increase in dysphagia. While it is true that a partial fundoplication adds 15–20 minutes to the time of operation, the potential benefits to the patient seem worthwhile. In addition, when proper suturing strategy is utilized, the performance of such a fundoplication will help to maintain the muscle edges in a separated position and prevent a healing and the recurrence of dysphagia secondary to healing of the muscular edges.

Other clinicians prefer the posterior partial or Toupet fundoplication, suggesting that this provides superior dysphagia relief when compared to the anterior Dor procedure [15]. No prospective randomized trial has been performed to compare these two partial fundoplication techniques; so, at present, the decision remains the surgeon's choice.

Early complications

Benign esophageal procedures can result in the occurrence of intraoperative and early perioperative complications similar to any other surgical procedures

such as deep venous thrombosis, wound infection, hematoma, pneumonia, wound dehiscence, or hernia. However, there are some immediate complications that are specifically pertinent to this type of surgery.

Perforation of viscus

Gastric or esophageal perforations have been reported to occur in less than 1% of benign esophageal procedures [17]. It occurs most frequently with achalasia though it is commonly recognized intraoperatively and immediately repaired. Perforations are more likely to occur in the esophagus than in the stomach due to the lack of serosa and the thinner wall. Gastric perforation along the greater curvature can occur if inadvertent damage occurs when dividing short gastric vessels using cautery or a harmonic scalpel. Care must be taken to divide the vessels several millimeters from the stomach lest full thickness gastric injury occur. Whenever a perforation is identified, immediate repair is indicated with viable tissue reinforcement (gastric fundus, omentum) utilized when possible.

Occasionally such complications will not be recognized until after surgery when the patient becomes febrile or develops leukocytosis upon the institution of oral intake. Such perforations occur more frequently in the reoperative setting probably due to scarring (which makes identification of tissue planes more difficult) and prior devascularization of the esophagus and/or stomach. In such cases, initial diagnosis may be suspected if free intra-abdominal air is seen, but confirmation requires utilization of a gastrographin swallow followed (if negative) by dilute barium radiography. Identification of a leak requires urgent reexploration with closure of the repair, reinforcement with viable tissue and, for many surgeons, placement of an adjacent drain in hopes of establishing a stable fistula should the repair prove unsuccessful. An antibiotic regimen must be instituted and include both Gram-negative and anaerobic coverage. Following repair, enteral feedings are held for 3–5 days after which repeat contrast radiography is undertaken to be certain the leak has healed prior to the institution of oral intake. If, for some reason, the diagnosis is delayed and at laparotomy the closure is suspect due to poor quality of the tissue, one should consider the placement of a jejunostomy tube as well.

Paraesophageal hernia and wrap migration

Acute intrathoracic herniation of a portion or all of a gastric wrap is reported in less than 2% of the patient's undergoing hiatal hernia repair [17]. Contributing factors may include an inadequate posterior crural closure as well as the occurrence of postoperative nausea with retching or vomiting. In those patients in whom early acute postoperative vomiting or retching occurs, a PA and lateral chest x-ray should be obtained to rule out the presence of a retrocardiac air bubble. Confirmation of the diagnosis may require the urgent performance of contrast radiography. When such a herniation is identified, it must be addressed on an emergency basis to minimize the chance for gastric ischemia and/or necrosis.

Gastric wrap herniation may occur in the absence of retching but will most commonly become symptomatic immediately. Such patients complain of severe dysphagia and/or odynophagia with regurgitation. The presence of these symptoms once again should lead to the performance of contrast radiogram so that early diagnosis and repair can be affected.

Splenic injury

Splenic injury occurs quite infrequently followed a hiatal hernia repair with a reported incidence of less than 1% [17]. It most commonly occurs during division of the short gastric vessels and it is usually immediately identified. A capsular repair or the utilization of topical hemostatic agents is indicated in hopes of avoiding a splenectomy. Occasionally, a splenic injury will not be immediately recognized, but will present as a sudden bout of hypotension or circulatory collapse days or a week after surgery following the rupture of a subcapsular hematoma. In such cases, urgent splenectomy is indicated.

Dysphagia

Dysphagia for solids is reported in up to 70% of the patients following the performance of a fundoplication. This is not surprising since the construction of an effective antireflux barrier requires an operation that significantly increases the lower esophageal sphincter pressure. Relaxation of the sphincter may be less than normal due to the static component of the gastric wrap and these factors lead to slowed esophageal emptying and the symptoms of dysphagia. The postoperative dysphagia most commonly lasts approximately 2–3 weeks, but in 5–10% of patients, it will extend beyond 6 weeks. In such patients, balloon dilation can be undertaken with a high rate of success. However, the failure of one or two balloon dilations usually indicates a more substantial problem.

When this occurs, one must suspect a significant technical problem. This might involve faulty patient selection (e.g., patient with profound dysmotility) or an intraoperative mistake (tight crural closure, tight fundic wrap, twisted wrap). If multiple dilations fail to relieve the dysphagia, then it is important to proceed with an appropriate workup, which usually includes repeat EGD in addition to a barium swallow and repeat manometry testing. In a small percentage of cases, this will lead to a recommendation for reoperation with conversion of a circumferential fundoplication to a partial fundoplication.

Flatulence

An increased incidence of flatulence will occur in approximately a third of patients undergoing an open fundoplication procedure [18, 19] and in approximately half those having a laparoscopic approach [8, 20–22]. In addition, associatedmany patients will complain of increased abdominal distention and epigastric fullness that is reported as the complication of meteorism. Once again, this has been reported both with open and laparoscopic procedures in approximately the same percentage of patients complaining of flatulence. However,

many of these same symptoms can be obtained for patients prior to operation if a careful questioning is undertaken [22, 23] and it is uncertain what role the operation actually plays in these problems. Such patients should be handled conservatively with dietary advice (avoid gas producing foods) and antigas medications (simethicone) as needed. In many patients, the symptoms will gradually improve over few months; however, such symptoms will persist after 1 year in up to 60% of patients [24, 25].

Gas bloat

A certain percentage of patients will complain postoperatively of an inability to belch, postprandial fullness, and a severe bloating sensation occasionally associated with dysphagia. This so-called "gas bloat" syndrome is felt to be due to combination of factors including a competent wrap, aerophagia, and possibly delayed gastric emptying due to unrecognized vagal nerve injury at the time of surgery.

This was a not infrequent complication following open fundoplication in the 1970s and 1980s and has been attributed to the performance of longer (4–5 cm) and tighter wraps being constructed at that time [26–28]. The evolution to shorter (2–3 cm), looser wraps may have decreased the incidence of gas bloat syndrome, but it is still reported at long-term follow-up (5 years) in 7–25% of patients following a primary fundoplication [1, 29]. Of interest however, like flatulence and meteorism, gas bloat-type symptoms can be obtained on careful interrogation of preoperative control patients [1]. These symptoms can almost always be treated by conservative management and rarely require reoperation.

Long-term complications

Recurrent symptoms

Although the long-term success rate of fundoplication is approximately 80–90% at 5 years, there is a significant incidence of recurrent symptomatology that may lead to reoperation. When recurrent symptoms do occur, they present as one or a combination of three specific symptoms; reflux symptomatology, dysphagia, and chest pain. The most common complaint in those patients undergoing reoperation following failed antireflux procedures is dysphagia (59%) followed by reflux (37%) and chest pain (8%) [17]. These symptoms, as well as some other minor ancillary symptoms (gas bloat, early satiety, and weight loss), may occur singly or in a variety of combination. Because none of these symptoms are pathognomonic for a specific mechanism of failure, all patients require a thorough workup including both anatomic and physiologic studies. Such studies should include a barium swallow, an EGD, a 24-hour pH test, and esophageal manometry. In occasional patients in whom suspicions arise regarding poor esophageal clearance or gastroparesis, an esophageal nuclear emptying scan and/or gastric emptying scan is indicated. Once all these tests have been performed, the reason for failure usually

Table 12.1 Major causes for failure following fundoplication.

Overly tight fundoplication
Overly tight crural closure
Disrupted wrap
Slipped wrap
Intrathoracic herniation of wrap
Paraesophageal fundic herniation
Twisted wrap

becomes obvious and one can select appropriate therapy, operative or otherwise.

The major causes for failure following fundoplication, whether performed for GERD or for paraesophageal hernia correction, can be seen in Table 12.1. Each may be accompanied by various combinations of symptoms with variable severity. It should be remembered that not all recurrent symptoms require operative intervention. In general, once the learning curve has been surmounted, reoperation rates are reported to be in the range of 3–13% [7, 17, 29, 30].

Wrap disruption

Disruption of a fundoplication is found intraoperatively in 14% of patients undergoing reoperation [17]. The most common complaint following breakdown of a fundoplication is recurrent reflux symptomatology. Such patients rarely complain of chest pain or dysphagia because there is no obstructive component. A wrap disruption with concomitant recurrent herniation occurs much more frequently following repair of a paraesophageal hiatal hernia, and has been reported in up to 43% of patients [31]. This is presumably because there is a tendency for crural repair breakdown due to the large size of the hiatus and the attenuated nature of the crural pillars.

The etiology of wrap disruption is difficult to determine but contributing factors have been suggested including obesity, chronic obstructive pulmonary diseases, excessive tissue fragility secondary to advanced age, steroids, or other immunotherapy and technical factors such as utilization of inappropriate suture material (absorbable suture or fine caliber suture) and inadequate mobilization of the fundus with resulting tension on the repair.

The diagnosis is usually easy to make either with contrast radiography or with an EGD. The radiograph will demonstrate a lack of the typical subdiaphragmatic constriction, which results from an intact fundoplication. Similarly, the EGD will fail to show the tight cylindrical wrap of gastric mucosa around the scope when a retroflex maneuver is performed.

Recurrent symptoms in some patients may be adequately managed by aggressive medical regimen including the combination of proton pump inhibitors, histamine receptor blockers, and antacids. However, patients refractory to such regimens can be considered for repeat fundoplication.

Prior to reoperation, a complete workup with pH and motility is warranted to be certain first that pathologic reflux indeed exists and that no changes in motility have occurred that would affect the chances for success with the subsequent procedure. In most patients, reoperation can be successfully performed, and experienced minimally invasive surgeons would attempt this laparoscopically. However, conversion to an open procedure is not infrequent and may occur in up to 50% of patients. In general, although the chances for long-term symptom relief are good, they are somewhat less than the chance of success after the primary procedure. It suggested that the 5-year success rate falls from approximately 85% with a primary repair to 75% with a reoperation [32, 33].

Slipped fundoplication

A fundoplication may also fail due to inappropriate wrap location on the body of the stomach rather than the distal esophagus. Such a wrap is termed as a "slipped Nissen" and has been reported in 14% of redo operations [17]. This lesion presents with symptoms slightly different from wrap disruption. Recurrent reflux can be the major presenting symptom as the small pouch of gastric acid secreting stomach is located above the surgically constructed valve. However, very often, patients also complain of obstructive symptomatology such as dysphagia and chest pain because the gastrogastric wrap impedes food passage.

Once again, the diagnosis can be made either by contrast radiography or by EGD. The radiograph will demonstrate the "hour-glass" deformity with a small pouch of stomach above the fundoplication defect.

The typical endoscopic appearance is one of a gastroesophageal junction and Z-line visible 2–4 cm above the narrowed area of the fundoplication. The retroflex maneuver reveals that the cylindrical wrap of gastric mucosa appears broader than the normal due to the fat that it is wrapped around the gastric body and not the smaller caliber esophagus. There are various purported etiologies for this abnormality, most of which are secondary to technical error. First and foremost, it is possible that in patients with foreshortened esophagus or in those operated upon by inexperienced surgeons, a gastrogastric wrap is performed erroneously at the time of the first operation when a tubular cardia is misidentified as the distal esophagus. Such patients typically complain of dysphagia postoperatively, which may transiently respond to dilation but which returns in short order and persists. Such patients may also complain of chest pain, regurgitation, and reflux symptomatology.

It is also possible for a slipped Nissen to occur after the performance of a complete fundoplication placed accurately around the distal esophagus. However, failure to include the esophagus in the fundoplication stitches or the utilization of inadequate "bites" can lead to slippage of the wrap and a telescoping down on to the body of the stomach.

Medical management with balloon or Savary dilation of the gastrogastric wrap can provide significant relief in a minority of cases. However, most

patients will require reoperation to achieve improvement. The procedure performed is deconstruction of the inappropriately located fundoplication with reconstruction of the wrap in a periesophageal position. In those patients in whom a foreshortened esophagus is found and inadequate intra-abdominal esophageal length is obtained despite circumferential dissection of the intrathoracic esophagus, a lengthening procedure such as a wedge gastroplasty is indicated.

Intrathoracic wrap migration

Yet another late complication is the intrathoracic herniation of an intact wrap, a finding noted in 36% of redo procedures [17]. While some have suggested it may be acceptable to construct a fundoplication and leave it intentionally within the thorax, in general, this has felt not to be optimal both because the wrap may be less competent in the negative pressure environment of the thorax and also because it is felt that crural closure around the stomach may lead to an increased incidence of ischemic complications and/or volvulus. While there is no large series that documents such complications following the intentional performance of the intrathoracic wrap, the acute migration of the intra-abdominal wrap through a crural closure can cause such symptoms. Because the crural closure has usually been calibrated to the size of a normal esophagus, the acute protrusion of a larger caliber stomach into the tightened crural closure can result in sudden acute pain, obstruction, and ischemia. When this occurs chronically over time, it leads to symptoms of intermittent dysphagia, chest pain, and occasional regurgitation. Although reflux symptomatology can be reported, it is less frequent because of the presence of an intact fundoplication.

The treatment recommended depends upon the presentation. Occasionally, such an intrathoracic fundoplication can be identified in the absence of significant upper gastrointestinal symptomatology. If indeed this occurs, then it is likely best not to recommend further surgery; however, in patients with significant symptomatology such as chest pain or obstruction, reoperation is indicated. Because of the intrathoracic nature of the lesion, a laparoscopic approach may not be successful and there is a relatively high incidence of converting to an open procedure. When a large portion of the stomach is intrathoracic, many chest surgeons will favor a thoracotomy approach because of the relative ease of mobilizing the stomach and esophagus from its mediastinal location. In such cases, one must carefully discern whether or not there is adequate intra-abdominal length of esophagus following mobilization. It is felt that one possible cause for intrathoracic migration is a subdiaphragmatic periesophageal wrap that was performed under tension with a taut esophagus resulting in upward traction on the wrap that drags it through the hiatus. If inadequate intra-abdominal esophagus is identified following complete mobilization, then a lengthening procedure such as Collis can be easily performed through the chest and is recommended.

Paraesophageal hernia

On occasion, paraesophageal herniation will occur when the posterior portion of the fundus situated immediately behind the esophagus herniates upward between the crural pillars and into the mediastinum. When this occurs, the mass of the stomach puts extrinsic pressure on the intrathoracic esophagus at the GE junction, thus leading to symptoms of dysphagia, chest pain, and, occasionally, early satiety. Early in the era of laparoscopic repair, crural closure was often felt to be optional and not always performed. Paraesophageal herniation was recognized increasingly, and since that time, posterior suture apposition of the crural pillars has become a routine during the performance of a laparoscopic fundoplication. In patients with a paraesophageal hernia in whom attenuated crural pillars are closed under tension, this can also be a late complication. Overall, this has been reported in 14% of reoperations for failed fundoplication [17]. In those patients in whom a very small paraesophageal hernia is present, the symptoms can be minor and such patients can be followed with serial contrast radiography. If the hernia enlarges and/or becomes symptomatic, prompt reoperation is indicated lest it progress to severe symptoms for which no medical therapy is effective. Technically suboptimal posterior crural closure can also lead to such herniation if the fascia overlying the crura is not preserved during dissection or if the sutures are tied too tightly and necrose the crural musculature.

Recurrent dysphagia following heller myotomy

Although the immediate success rate for a laparoscopic myotomy as treatment for achalasia is 90%, there are late complications that can occur. Recurrent dysphagia may occur for any number of reasons including excessive scar formation at the site of the myotomy, inadequate distal extent of the myotomy, reapposition and healing of the cut muscular edges, and paraesophageal herniation of the gastric fundus (may occur posteriorly in a Toupet or anteriorly in a Dor fundoplication). As is necessary with the workup for failed fundoplication, complete imaging and physiologic testing is indicated. This includes contrast radiography, EGD, 24-hour pH testing, and esophageal manometry. Most patients who do present with such complications will present with recurrent dysphagia that should initially be managed with attempts at pneumatic balloon dilation. If these indeed fail and symptoms persist, then operative repair is indicated. In patients with severe dysphagia in whom a grossly dilated (greater than 6 cm) sigmoid-shaped esophagus is present, esophagectomy with gastric pull-up or colon reposition has been shown to be effective therapy for dysphagia once an initial myotomy has failed [34, 35].

A small percentage of patients will present with reflux symptoms or stricture due to the combination of an ablated lower esophageal sphincter and the poor esophageal clearance secondary to aperistalsis. In most cases, such patients can be managed with aggressive antisecretory therapy including high doses of proton pump inhibitors, bedtime histamine receptors, and antacids as needed. Reoperation with fundoplication can be entertained but the wrap

must be partial rather than circumferential to prevent serious dysphagia. If not followed closely, patients who fail medical therapy can present with a peptic stricture that would initially be carefully and slowly dilated. However, if the peptic stricture recurs, one must consider the possibility of resection and conduit interposition, as the combination of the gross reflux with inadequate esophageal clearance would likely condemn the patient to continued stricture formation with medical therapy alone.

Conclusions

Surgery for benign esophageal disease is successful in a high percentage of patients whether performed for GERD, giant paraesophageal hiatal hernias, or achalasia. Long-term success rates in the range of 85–90% are obtainable for each of these three conditions when the surgery is performed for the appropriate diagnosis by a well-trained surgeon.

As with disorders in any other organ, an accurate diagnosis is critical to achieving the high success rate following the surgical procedure. Thorough evaluation with both imaging and physiologic tests should be undertaken so that both patient and surgeon can be assured that a correct diagnosis has been made. These conditions are best treated by surgeons experienced in the both open and laparoscopic management of esophageal disease; such surgeons not only possess thorough knowledge of the natural history and pathophysiology but also will have mastery over the maneuvers and surgical techniques necessary to achieve a high rate of success no matter what is encountered intraoperatively. However, no matter how experienced the surgeon, postoperative complications will occasionally occur both in the early and late phase. These complications require a thorough workup and should ideally be addressed by specialists in the medical and surgical management of esophageal disease.

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CHAPTER 13

Complications of Mediastinal Procedures

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Mediastinal surgery is almost always safe and performed with minimal, if any morbidity. This is perhaps related to the fact that mediastinal surgery does not impair respiratory capacity as pulmonary resection does and does not place an occasionally tenuous stomach conduit with an esophageal anastomosis in the field after esophagectomy. Complications of incisions are discussed in another chapter. In this chapter, avoidance and treatment of complications will be discussed for each important mediastinal procedure.

The initial decision making regarding the diagnostic evaluation of the mediastinal mass or cyst is critical for avoiding complications. The beginning point is almost always a contrast-enhanced chest computed tomographic scan (CT). CT allows delineation of the mass or cyst, determination of invasion of and relationship with surrounding structures, examination of the interior of the mass for homogeneity, the presence of calcifications, necrosis or hemorrhage, and Hounsfield unit measurement. As well, associated lymphadenopathy can be detected. For example, proper interpretation of the chest CT should almost always allow the astute thoracic surgeon to diagnose an anterior mediastinal lymphoma and proceed down the biopsy route as opposed to resection for a presumed thymoma. Magnetic resonance (MR) imaging allows the differentiation of cyst from solid and provides the best imaging of nervous tissue, most important for investigating if there is intraspinal extension of a neurogenic tumor. Once a clinical diagnosis is made and a decision for resection is taken, the proper approach must be planned. The mediastinum can be approached in many different directions and all approaches have their pros and cons. Most important to realize now is when video-assisted thoracic surgery (VATS) is likely to be successful and when it is likely to put the patient at risk because of inadequate exposure. Not every tumor or cyst can be cleanly removed by VATS and sometimes a large incision is best—this decision is a sign of good judgment rather than one of weakness.

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Mediastinoscopy

Mediastinoscopy is usually performed without incident with a reported complication rate of 0.6–1.1% and a mortality of only 0.05% [1, 2]. Probably, the most important consideration in avoiding complications is experience. Whereas mediastinoscopy is routine for some surgeons with all lung cancer patients, others use it rarely and thus are less facile with all the nuances needed to stay out of trouble. The modern use of video mediastinoscopy has enhanced the ability to teach this procedure, which should lead to more trained surgeons. Several reports have documented the safety of redo mediastinoscopy in skilled surgeons hands. Nonetheless, the tissue planes are not normal and a redo procedure is definitely harder and more likely to lead to injury to an adjacent structure. Mediastinoscopy has also been reported after induction therapy for lung cancer with generally safe results. My own experience is that it is not much more difficult after induction chemotherapy, whereas it is exceedingly challenging after induction chemoradiotherapy because of the inflammatory changes in the mediastinum. I almost never do it when radiation is included in the induction program and instead opt for another route if a particular lymph node needs to be sampled. Either endobronchial ultrasound (EBUS) or endoscopic esophageal ultrasound (EUS) can reach any node that mediastinoscopy can reach.

When cervical mediastinoscopy is performed, the patient should be properly positioned on the table with the head maximally extended such that good access can be achieved near the carina. The anterior chest should always be prepped into the field in case emergent access to the mediastinum through a sternotomy to control an injured blood vessel is required. One should not try to enter the mediastinum with a finger in a plane superficial to the pretracheal fascia as that can lead to injury of the innominate artery. The mediastinoscope should only be inserted underneath the pretracheal fascia and not advanced until the surgeon's finger, dissecting sucker, or forceps makes a space for it. No biopsy should be performed before sufficient dissection has been performed for the surgeon to have absolute certainty about precisely what tissue is being targeted. For example, if there is oozing of blood from the dissection sufficient to obscure the tissues, it must be controlled so that visualization is not compromised. A few minutes of packing with a gauze sponge will usually suffice to accomplish this goal. Nodes should be at least partially dissected out to ensure they are not vascular structures prior to biopsy. If there is any concern, a needle aspiration test should be done of the node prior to biopsy. The left side of the trachea always contains the recurrent laryngeal nerve and sometimes the esophagus: both of these structures must be avoided. When doing a node biopsy, one must not exert too much force when pulling for fear of tearing an attached vascular structure.

The most feared, albeit rare, complication is major bleeding. The incidence in the three largest series of mediastinoscopies has been 0.1%, 0.3%, and 0.4% [1–3]. Vessels involved include the innominate artery, aorta, azygous vein,

superior vena cava, and the pulmonary artery. The most frequently involved node when a major hemorrhage occurs is the 4R node. Treatment options include temporary packing with a gauze sponge or rubber dam, endoscopic clip application (usually of an azygous vein injury), sternotomy and repair, and thoracotomy and repair. Dark blood indicates venous or pulmonary artery injury and red blood indicates an arterial injury. The location where the biopsy occurred leads to the correct diagnosis of which vessel was injured. Sternotomy is done either for access to the vascular injury or when a lung cancer is on the left and resection is contemplated after vascular repair. Right thoracotomy can be done if packing controls the bleeding and a right lung resection is planned after vascular repair. Obviously, simultaneous lung resection of a lung cancer is only done if the patient is quite stable after repair and resection is oncologically prudent.

Other complications of mediastinoscopy include inadvertent injury to the trachea or bronchi, esophagus, recurrent laryngeal nerve, peumothorax, stroke, and arrhythmias. Recurrent nerve injuries after mediastinoscopy generally should be observed first unless one knowingly transected the nerve as function may return with several months of waiting if the nerve is only injured. Options for treatment of persistently symptomatic unilateral cord paralysis include Teflon injection of the cord for temporary relief or medialization of the cord for permanent relief [4]. Airway injuries and esophageal injuries require operative repair.

Thymectomy for myasthenia gravis

One of the most important factors in avoiding complications in patients scheduled for thymectomy is an accurate diagnosis by an experienced neurologist. The diagnosis rests on the combination of the history of fatigable weakness of characteristic muscle groups, the neurologic exam, pharmacological, electrophysiological, and serological testing. The most important test is the detection of antibodies to the acetylcholine receptor, which are present in about 85% of patients with myasthenia gravis. The next important step in avoiding complications is close collaboration with the treating neurologist to maximize the preoperative condition of the patient. If there is significant bulbar or respiratory muscle weakness, then typically either plasmapheresis or intravenous immunoglobulin (IVIG) therapy is done to maximize the condition of the patient. It is not clear if one therapy is superior to the other and most institutions have a preference for one or the other. Older patients or those with heart disease or poor vascular access tend to have problems with plasmapheresis. One randomized study compared IVIG to plasmapheresis in 87 patients and found essentially equal efficacy but IVIG therapy had fewer side effects [5]. A retrospective series suggested that plasmapheresis was superior to IVIG in patients with myasthenic crisis [6]. Plasmapheresis lasts only several weeks and takes anywhere from 1 to 2 weeks to show significant improvement. IVIG results in

improvements in about two-thirds of patients, lasts several weeks, and takes from 1 to 4 weeks to show significant improvement.

The surgical complications of thymectomy relate in large part to the operative approach to thymectomy. In transcervical thymectomy, the innominate vein is at risk, as well as the phrenic nerves and pleura. Large series of transcervical thymectomy report very low complication rates [7]. VATS thymectomy, usually performed on the right side, can be associated with inadvertent lung injury, great vessel injury, phrenic nerve injury, pneumothorax, and intercostal neuralgia [8]. Transternal thymectomy complications include sternal wound infection, atelectasis, pneumonia, phrenic nerve injury, pericarditis, and arrhythmias [9]. Residual thymus leading either to a thymoma or recurrent/persistent myasthenia gravis is possible after any type of thymectomy but seems to be more likely after more minimally invasive type of resections [10]. Experience, knowledge of anatomy, meticulous dissection around danger points, and consideration of conversion to an open approach if a minimally invasive technique is used are key points in avoiding complications.

Thymomas

Resection of a thymoma, usually through a sternotomy approach, is a generally straightforward procedure with relatively rare complications and a mortality of about 1% [11]. Small thymomas can also be resected via a transcervical approach or a VATS approach, albeit with an ever-present concern of incomplete resection or inadvertent breech of the capsule spilling tumor into the wound or chest cavity. In general, I almost always favor a transternal approach to facilitate a complete resection and minimize the chance of inadvertent capsular tears. The most common reason I consider a minimally invasive approach is when there is a small (1–2 cm) nodule in the thymus and the differential diagnosis includes benign considerations such as lymph node tissue or thymic cyst. I have reviewed cases from other centers that favor a minimally invasive approach where stage I thymomas are removed by VATS but then return with pleural space dissemination within 2 years. It seems to me that inadvertent capsular violation must have occurred in these cases as stage I thymomas should not recur in that fashion. For that reason, I continue to favor an open approach even for small thymomas.

Complications of the transternal approach include sternal wound infection, atelectasis, pneumonia, arrhythmias, phrenic nerve injury, pericarditis, and tumor recurrence. Pericarditis occasionally occurs after extensive thymoma resections and can be quite troublesome. The most important aspect is to consider the diagnosis when a patient presents with fever, chest discomfort, and lassitude after a resection. Ascultation of a rub, ECG findings consistent with pericarditis and echocardiographic findings consistent with pericarditis all help clinch the diagnosis. The initial treatment is with a nonsteroidal anti-inflammatory agent (NSAID) with prednisone reserved for failures of NSAIDs.

Thymomas should be resected en-bloc to minimize recurrences. This may necessitate resection of attached lung, mediastinal fat, pericardium, or the great veins. Many surgeons are reluctant to resect the pericardium underneath the thymoma for reasons that I do not understand as there is little downside to pericardial resection. This margin can often come back with microscopic capsular invasion, which then leads to mediastinal radiation that has significant late complications [12]. When I review the preoperative CT scan and I see abutment of the tumor with no intervening fat on the anterior pericardium, I plan on a pericardial resection. I do not sharply dissect it off the pericardium and violate one of the key principles of cancer surgery. In patients without myasthenia gravis if one phrenic nerve is involved, I will resect the involved nerve. This action is more problematic in patients with myasthenia as respiratory failure after operation can lead to severe morbidity and death. Patients with favorable tumor biology and mild to moderate myasthenia usually have the nerve sacrificed, whereas in those with resections likely to be incomplete or with severe myasthenia, the nerve is preserved and marked with clips for postoperative radiation. If a nerve is resected, the question comes up as to whether the diaphragm should be plicated. I almost always leave it alone and have not had to reoperate for symptomatic paralysis but others feel that the diaphragm should be immediately plicated. It is unclear which strategy is best.

If the innominate vein is involved, I resect it and elevate the left arm postoperatively. If the superior vena cava (SVC) is involved (and this can usually be determined preoperatively based upon the CT scan), then I plan to resect it en-bloc with the tumor. Complications of SVC resection can be minimized with careful preoperative and intraoperative planning [13]. IV access is required in the lower body, reverse Trendelenburg positioning is used, IV heparin is administered, only one vein is reconstructed if the confluence is involved (usually the right as it is usually larger), and the clamp time is kept as short as possible with an expeditious vascular anastomosis. I always use ringed PTFE grafts and have never had postoperative thrombosis. I place patients on 81 mg aspirin for life and coumadin for 1 month only. Complications of SVC replacement include cerebral edema, stoke, blindness due to retinal vein thrombosis, and graft thrombosis leading to acute SVC syndrome.

Mediastinal nonseminomatous germ cell tumors

Patients with suspected nonseminomatous germ cell cancers should have a serologic diagnosis by measurement of the serum tumor markers beta human chorionic gonadatropin and alpha fetoprotein. A fine needle aspiration can be done for reassurance and also adds valuable prognostic information. Major diagnostic operations should be avoided so that life-saving chemotherapy is not delayed. Most patients who have a nonseminomatous germ cell cancer will require resection of a residual postchemothrapy mass. The previous standard regimen contained bleomycin, a pulmonary toxin that led to increased postoperative pulmonary complications. Measurement of DLCO preoperatively

to gauge risk, minimizing high inspired oxygen concentrations during the operation, and keeping intravenous fluid administration to a minimum were the standard measures employed to reduce pulmonary complications. The most common modern regimen is cisplatin, etoposide, and ifosphamide (VIP) and is not associated with pulmonary toxicity. The largest modern series of nonseminomatous germ cell cancer resections reported on 158 patients over 25 years [14]. Complications, primarily pulmonary, occurred in 36 (23%) patients and the mortality was 6% (nine of ten died of respiratory failure; the other dies from a pulmonary embolism). The complications included respiratory failure in 19 patients, prolonged air leak in 7 patients, and delayed tamponade in 4 patients. Respiratory complications have significantly decreased with the use of the modern VIP chemotherapy regimen. Major pulmonary resections were thought to be the most important factor leading to respiratory failure and death. The resection of these patients needs to take into account the typical postchemotherapy pathology that includes an outer zone of fibrosis that allows resection of these masses away from important adjacent structures rather than true en-bloc resections. Lung shaving (and thus lung-sparing) operations should generally be done as the typical attachment to the upper lobes is very superficial and the fibrotic capsule rarely contains viable tumor. These close margins can be checked with intraoperative frozen section control.

Neurogenic tumors

Resection of typical benign posterior mediastinal neurogenic tumors is usually quite straightforward with rare complications. Whereas thoracotomy was routinely performed in the past, many of these tumors are now safely removed by VATS. The most important preoperative consideration is recognizing intraspinal extension of the tumor if it abuts the intervertebral foramen—the so-called "dumbbell" tumor. This is best done with MR imaging. If present, consultation with a neurosurgeon is required and a joint operation is planned [15, 16]. Some dumbbell tumors can be resected with VATS for the chest portion, thus minimizing pain from the exposure for the resection. The most important intraoperative considerations involve the safe control of the proximal intercostal artery and nerve. Unipolar cautery should not be used on these structures as heat and current can be transmitted to the spinal cord leading to severe neurologic sequela. Bipolar cautery is safe to use on small vessels but should not be used on the nerve itself. If control of an intercostal artery is lost at the intervertebral foramen level, unipolar cautery should not be used for the previous reason cited, nor should packing of the foramen with oxidized cellulose be done as this can lead to an epidural hematoma with compression of the spinal cord [17]. A neurosurgeon should be requested who can enlarge the foramen with drilling out of the surrounding bone to allow safe control of the vessel. Other complications include hemothorax, atelectasis, pneumonia, and intercostal neuralgia.

Paraganglomas

Paragangliomas are rare tumors that can occur in the posterior or middle mediastinum. The most important preoperative consideration is consideration of the diagnosis and avoiding a biopsy if they are functionally active as biopsy may precipitate a hypertensive crisis [18]. Patients should be prepared for either biopsy or resection with alpha and beta blockade to prevent this problem. If they are located in the middle mediastinum, the vascular supply is often from the coronary circulation; so careful consideration of this fact is important in planning and conducting the resection. These tumors tend to be quite vascular; so careful dissection and vascular control are prudent when resecting these tumors. Rarely, they may require embolization before resection to minimize intraoperative bleeding.

Bronchogenic cysts

Bronchogenic cysts can be very straightforward to remove with just minimal attachments to the lung, airway, or mediastinum with a resultant rare risk of complications. Alternatively, they can be very adherent to the airway or actually make up the wall of the airway leading to more difficult decision making and surgery. Review of the preoperative CT scan will alert the surgeon to potentially difficult cases where there is extensive abutment of the airway so that proper planning can occur prior to operation. Usually, the best option when a portion of the cyst is one with the wall of the airway is to leave that portion of the cyst and do a subtotal resection. The epithelium of the cyst can then be fulgurated to destroy the epithelium. Another option is to resect the entire cyst wall and replace it with autologous pericardium if the resulting defect is not too big [19]. This must be an airtight closure to prevent a bronchopleural fistula. Many cysts have an extensive inflammatory adherence to all surrounding structures in the mediastinum, which makes safe resection of them more challenging than initially thought. Most cysts are initially approached by VATS these days as the majority can be safely resected by VATS. Conversion to open thoracotomy should be considered if the surgeon starts becoming uncomfortable in the endoscopic dissection of a difficult bronchogenic cyst. All surrounding structures are at risk, including the lung, airway, esophagus, azygous vein, phrenic nerve, thoracic duct, and aorta. Complications are relatively common in patients with symptomatic presentations in recent series [20, 21]. One series of 86 patients reported no deaths and a 14% incidence of intraoperative complications (vagal division, bronchial injury, and esophageal injury) and 9% incidence of postoperative complications (respiratory failure, hemothorax, atelectasis, wound infection, and Horner's syndrome) [21]. The other series of 69 patients (both adults and children) had a single mortality from a compressive cyst in a newborn. Complications were recorded in 13% of patients and included pneumonia, chylothorax, and phrenic nerve paralysis.

Esophageal duplication cysts

Resection of esophageal duplication cysts is also usually straightforward and usually done by VATS. If intraoperative difficulties are encountered, there should be little hesitation to open and obtain better exposure. If cysts are not infected and otherwise uncomplicated, they usually shell out of the esophageal wall fairly easily until the submucosa of the esophagus is reached. There is frequently an intimate connection between the wall of the cyst and the submucosa resulting in entry of the lumen of the esophagus. This is usually not an issue as long as it is recognized and repaired properly in two layers. If there is any concern about the repair, another layer closure should be done with a viable tissue flap, like the pericardial fat pad. All surrounding structures are at risk, including the lung, airway, esophagus, azygous vein, phrenic nerve, thoracic duct, and aorta. Complications are quite rare in recent series [22, 23].

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CHAPTER 14

Complications of Pleural Operations and Procedures

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Introduction

The pleura is a thin serous membrane that covers the lung, mediastinum diaphragm, and chest wall. The pleura consists of two cellular layers: a mesothelial monolayer facing the pleural space and an underlying connective tissue matrix. It is divided into two anatomic layers, a visceral layer, which envelops the pulmonary parenchyma and includes interlobar fissures, and a parietal layer, which covers the ribs, diaphragm, and mediastinum. The virtual cavity between the two layers is the pleural space. Under normal circumstances, the pleural surfaces are tightly coapted due to the negative pressure in the pleural space and are separated only by a small amount of fluid (0.1–0.2 mL/kg) [1]. The pleura functions to mechanically couple the lungs and chest wall, facilitating respiration.

Diagnosis

Avoiding complications begins with accurate and timely determination of relevant pathology. Even though physical examination and medical history often suggest the nature of the disease, radiographic imaging is an important adjunct in the evaluation of patients with suspected pleural disease. Conventional erect chest radiographs can demonstrate pneumothorax, pleural-based fluid collections, and pleural thickening. The high-resolution axial imaging provided by chest computed tomography (CT) scans allows for detailed assessment of pleural-based disease (Figure 14.1) and is recommended for all patients with complex pleural space problems. Ultrasonography has a role in guiding percutaneous diagnostic and therapeutic procedures such as drainage of free or loculated fluid collections. Magnetic resonance imaging (MRI) is of use in determining the resectability of malignant mesothelioma or Pancoast tumor [2].

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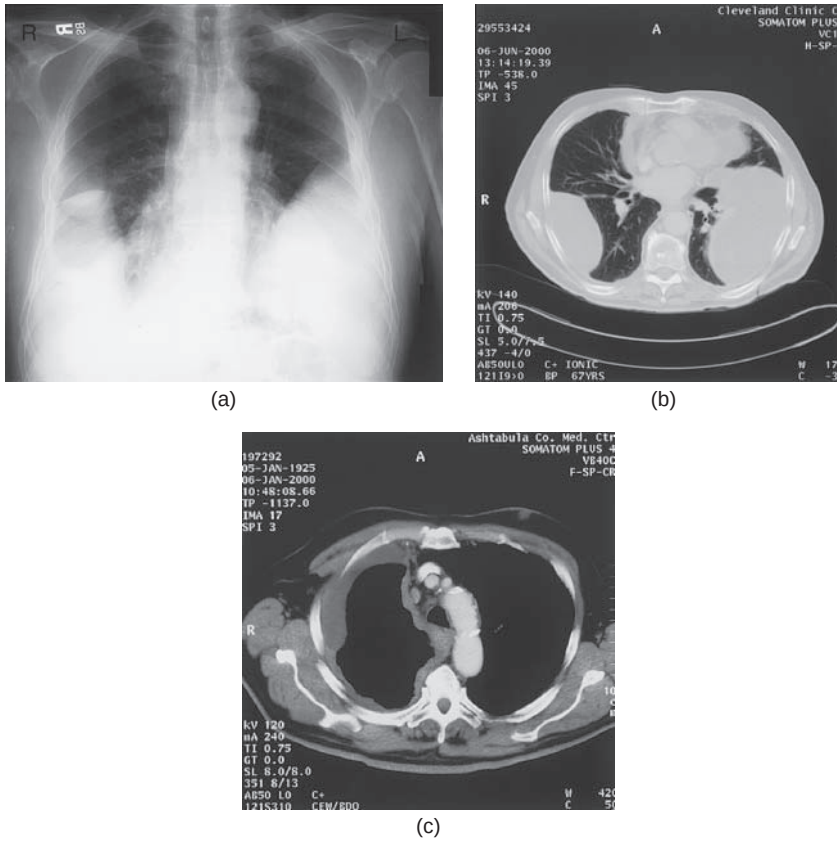


(a) (b)

(c)

Figure 14.1 (a, b, c) Chest computed tomography scans provide excellent anatomic detail of pleural-based disease. (a) Chest-x-ray demonstrates bilateral complex pleural effusions. (b) From the same patient whose chest x-ray is shown in Figure 14.1a. (c) Circumferential pleural thickening characteristic of malignant mesothelioma and fibrothorax.

Surgical evaluation of the pleural space

Pleural effusion

Pleural effusion is the most common clinical manifestation of pleural disease and the most frequent indication for pleural-based surgery. Pleural fluid is constantly secreted, mostly by filtration from the microvessels in the parietal pleura and is reabsorbed by lymphatic stomata in the parietal pleura. The movement of fluid is governed by three factors: the permeability coefficient of the pleura, the difference in hydrostatic pressures, and the difference in osmotic pressures across the pleura. Pleural effusions develop when there is imbalance between hydrostatic (congestive heart failure) and oncotoc (hypoalbuminemia) gradients, migration of fluid from an extravascular source (ascites), excessively negative pleural pressures (atelectasis or trapped lung),

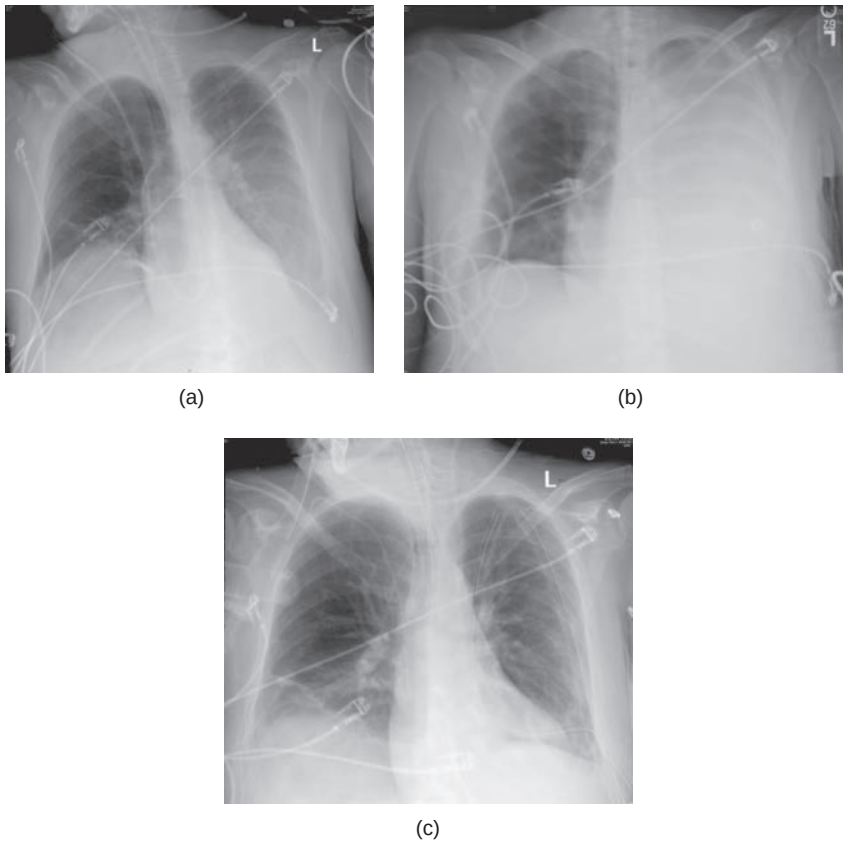
impaired lymphatic drainage (lymphangic carcinoma), or increased microvascular permeability (pneumonia, pleural carcinomatosis). Pleural fluid collections are divided into transudates and exudates. Exudative effusions have a much higher protein content (pleural protein concentration to serum protein concentration of greater than 0.5) and a higher LDH concentration (pleural fluid LDH to serum LDH ratio greater than 0.6) [1]. The etiologies of exudative pleural collections include infection, systemic inflammatory illness, and neoplasm [1, 3]. Exudative effusions often require interventional procedures for both diagnosis and therapy. Medical therapy is typically the mainstay for treatment of transudative effusions.

Chest x-ray usually reveals pleural effusions of 200 mL or more as blunting of the costophrenic angle. As the amount of fluid increases, greater opacification of the hemithorax is noted. Massive effusions are most commonly malignant. A CT scan helps differentiate simple effusions from complex collections. Enhancing of the pleura on a contrast-enhanced CT suggests the presence of empyema (double pleura sign). Diffuse pleural thickening or nodularity suggests a malignant process.

Thoracentesis

Thoracentesis with pleural fluid analysis is the most useful test in differentiating possible causes of the effusion and can be performed at the bedside or in the outpatient clinic. Pleural fluid analysis establishes the diagnosis in 50–87% of cases [4]. Large or free-flowing effusions can be safely aspirated. Bedside ultrasonography reliably detects loculations, guides safe thoracentesis, and decreases procedure-related complications. Complications include a 3–20% incidence of pneumothorax [4]; in most instances, the pneumothorax is small and does not require intervention. Larger pneumothoraces can be drained with a percutaneous catheter or a small-bore chest tube. Other complications of thoracentesis include pleural space infection, subcutaneous hematoma, and hemothorax (Figure 14.2). Most complications can be avoided by observing a few simple safeguards and utilizing ultrasonography to localize the effusion and guide the needle.

Complete opacification of a hemithorax can be secondary to a large effusion but this radiographic appearance can be mimicked by consolidated or atelectatic lung secondary to pneumonia, tumor, or mucus impaction (Figure 14.3). Thoracentesis or chest tube insertion in this situation may result in parenchymal injury. Radiographic clues such as mediastinal shifting (toward collapsed lung, away from a pleural effusion), rib space crowding, and volume loss may help distinguish between effusion and atelectasis or consolidation. Ultrasound and chest CT scan are helpful in further characterizing the process and often direct appropriate therapy. Bronchoscopy is only indicated in the workup of an undiagnosed pleural effusion in the presence of lung consolidation or hemoptysis [5], as the diagnostic yield in the absence of either is only 4% [6].

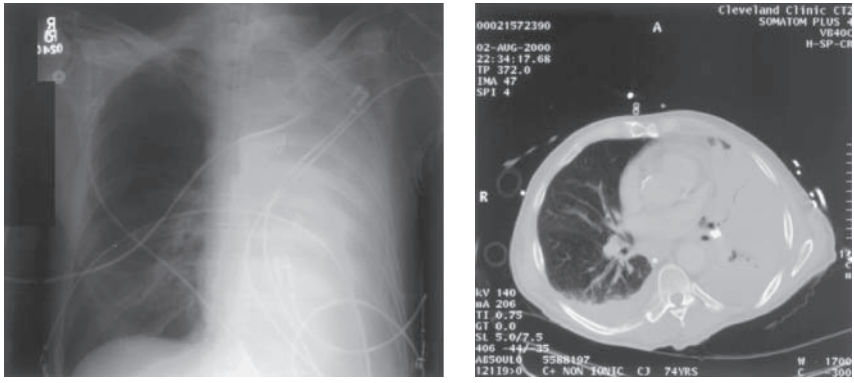


(a) (b)

(c)

Figure 14.2 (a) Left-sided hemothorax following thoracentesis for pleural effusion. (b) The patient developed hypotension, respiratory distress, and complete opacification of the hemithorax. (c) Chest x-ray following thoracoscopic evacuation of clotted hemothorax; note complete resolution and correct placement of chest tubes.

All fluid collections should first be located with the fine gauge needle utilized to deliver local anesthesia, prior to placement of a large needle or catheter for aspiration. Very rarely will lung puncture with the finer needle result in pneumothorax. Free-flowing effusions should be accessed in the posterior axillary line. The chance of intercostal vessel injury is increased when more posterior attempts are made due to the narrower intercostal spaces. One or two fingerbreadths below the scapula tip, while the patient is placed in a seated position and draped over a padded Mayo stand, will invariably place the catheter in the lower aspect of the chest. Attempts at a lower access site can result in liver or splenic puncture. Loculated effusions require adequate localization prior to thoracentesis by sonography or by chest CT. Serial thoracentesis may be necessary for high-volume simple effusions. Alternatively, a small-bore catheter (8.5–16 French) can be left in place and used to regulate the egress of fluid.



(a) (b)

Figure 14.3 Comparison of (a) plain chest x-ray and (b) chest computed tomography (CT) from a patient with opacification of the hemithorax. The CT scan demonstrates that the x-ray finding represents lung collapse, and not a large pleural effusion.

Tube thoracostomy

Most chest tubes are made of silastic and have multiple side holes, a radiopaque stripe, and vary in diameter. These tubes are firm yet pliable; they induce minimal skin or pleural reaction, and they are inexpensive. In patients with pneumothoraces, either a catheter (12–14 French) or a small chest tube (16–24 French) is sufficient. For patients with hemothoraces, malignant effusions, or empyemas, larger tubes (28–40 French) are recommended because the fluid being drained tends to occlude smaller tubes.

The ideal site of insertion of a chest tube is at the safe triangle over the anterior or middle axillary line (Figure 14.4). This triangle is bounded by

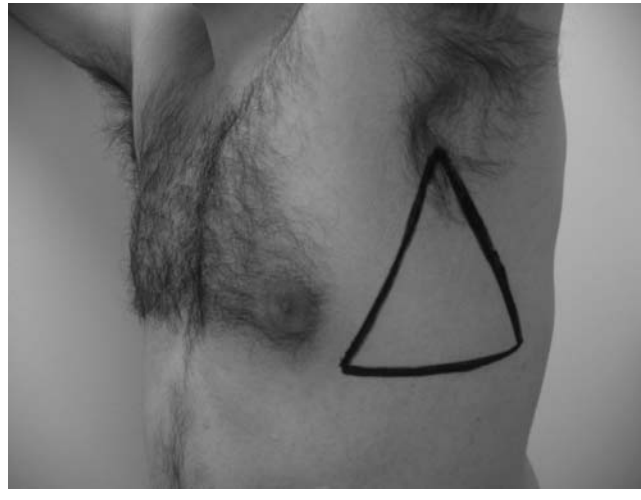


Figure 14.4 Ideal insertion place for chest tube thoracostomy. The “safe triangle” is bounded by the pectoralis major fold, the edge of the lattisimus dorsi muscle, the axilla, and the nipple.

the pectoralis major fold, the latissimus dorsi muscle, the apex of the axilla, and the nipple. In this location, the thickness of the chest wall is minimal, with no muscles other than the intercostal muscles. Percutaneous insertion of small-bore catheters can be performed anteriorly in the second or third intercostal space, midclavicular line, but is not recommended for chest tubes because dissection through the pectoralis major muscle can result in pain and hematoma.

Once the site of placement for the tube is selected and anesthetized, a 2-cm skin incision is made and blunt dissection with a curved Kelly clamp is carried over the superior border of the rib. In cases of moderate to large pneumothorax, there is little risk of injury to the lung parenchyma. In all other situations, the pleural space should be first inspected bluntly with the index finger to confirm that the parietal pleura has been penetrated and to avoid injuries to the underlying lung. The tube should be directed posteriorly and superiorly, parallel to the ribs, and not straight in like a spear. This will result in the tube lying along the spine with its tip in the apex of the chest and minimize the possibility of an intraparenchymal or interlobular placement. An alternative technique of insertion is the trocar method, but there is increased risk of injury to the underlying lung or other intrathoracic structures.

Chest tubes should never be clamped other than to rule out an air leak from the system or to change the drainage system. Clamping during transportation of the patient can be catastrophic because of potential tension pneumothorax. When the functional status of the tube is in question, observation of fluid oscillation in the water seal or in the tubing is important. Oscillations that are synchronous with respiratory movements (tidiling) indicate tube patency. If there are no oscillations, the tube may be occluded, or there may be complete reexpansion of the lung. Increased oscillations are a sign of high negative intrapleural pressure, often associated with atelectasis, incomplete lung reexpansion, trapped lung, or residual pleural space after lung resection.

Complications of tube thoracostomy are depicted in Table 14.1. Complications rates vary from 2% to 15% and can be classified as insertional, positional,

Table 14.1 Complications of tube thoracostomy.

Insertional
Intrathoracic organ injury: lung, heart, mediastinum, vessels
Chest wall: intercostal vessel injury
Intra-abdominal injury: liver, spleen, stomach, diaphragm, colon
Positional
Extrathoracic (above ribs)
In the fissure
Kinking
Last hole outside chest
Infective
Cellulitis
Empyema

or infective [7]. A difference in complication rates has been noted between surgeons and other physicians [7–9]. Complications include lacerations of the lung, intercostal artery, esophagus, heart, pulmonary artery, stomach, liver, spleen, and diaphragm. An effort should always be made to avoid misplacement of chest tubes, either extrapleurally in the soft tissues of the chest or below the diaphragm. The last hole of the tube must be well inside the pleural space to avoid surgical emphysema or accumulation of fluid in the chest wall. Dislodgment of chest tubes can occur in obese patients with thick and floppy chest walls.

Diaphragmatic and intra-abdominal injuries are more likely to occur when the diaphragm is elevated, such as in obese individuals, diaphragmatic paralysis, or after pneumonectomy. Although any organ in the upper abdomen is at risk, the spleen, stomach, and liver are most often injured. The majority of these injuries can be prevented by avoiding placing the tube outside the safe triangle and by finger exploration of the wound to confirm intrapleural insertion.

Intercostal vessel injury is uncommon and is related to tube placement close to the inferior border of the rib. It is more common in older patients whose intercostal arteries are more tortuous. Massive hemorrhage can be secondary to injury to the vena cava or the heart. These complications are fortunately rare and almost always due to forceful trocar insertion of a chest tube. If this is suspected, one should not remove the tube at the bedside but rather clamp it and bring the patient to the operating room for immediate repair.

Surgical emphysema can occur shortly after tube insertion or during the following days. It is secondary to inadequate drainage of the pleural space as air reaches the subcutaneous tissues through the perforated pleura at the incision site. The problem may be due to improper location of the tube in the pleural space (e.g., within a fissure), occlusion of the tube, a large air leak, or placement of a side hole within the soft tissues of the chest wall. The chest x-ray should be inspected for tube misplacement and the entire drainage system thoroughly checked. CT is more accurate than chest radiograph to establish the diagnosis of tube malposition [10–13]. If the whole system is airtight, the tube is functioning and well placed, the level of suction should be increased. If this does not resolve the problem, a new tube should be inserted.

Reexpansion pulmonary edema (RPE) is a rare but potentially lethal complication that is usually unilateral and develops within 1–24 hours after drainage. Several clinical factors are thought to predispose to the occurrence of this problem: the chronicity (>3 days) of the lung collapse, whether it is secondary to an effusion or undrained pneumothorax, the rapidity with which reexpansion occurs, and the use of negative pressure for lung reexpansion [14, 15]. Preoperative drainage of a large effusion, either by thoracentesis or a small-bore catheter (8.5 French), may prevent the occurrence of RPE in patients undergoing tube thoracostomy or thoracoscopy for recurrent or malignant effusions. The pathophysiology of RPE is believed to be an increased capillary leakiness resulting from the mechanical stress applied to the reexpanding lung.

The treatment of RPE is supportive with mechanical ventilation, if necessary. If the patient survives more than 48 hours, full recovery is the norm. Mortality rates range from 0% to 20% [14]. Prevention is the key. Even though most patients can withstand rapid evacuation of large effusions without sequelae, it is prudent to adopt a conservative approach and limit the rapidity with which effusions are drained (e.g., stop draining for a period of 1–2 hours with every liter of fluid evacuated), and terminate the procedure if the patient develops chest discomfort, distress, or a cough.

Chest tubes can be removed safely during inspiration, exhalation, or during a breath hold, but must be removed rapidly to minimize the length of time. There are tube side holes both in the pleural space and outside the patient. Even a small pneumothorax after removing chest tubes can result in suboptimal outcome. Every effort should be made to avoid this situation by rapid tube removal and using a two-member team to remove the tube and to tie the U stitch.

Pleuroscopy and thoracoscopy

The applicability of thoracoscopy has steadily increased since its inception 80 years ago. Video assistance, first reported in 1991 [16], has facilitated the dissemination of the technique. The most frequent application of thoracoscopy is evaluation of pleural effusion. For one-fifth of all pleural effusions, the etiology remains undetermined after thoracentesis and/or percutaneous pleural biopsy [17, 18]. Thoracoscopy can supplant more invasive approaches and is frequently both diagnostic and therapeutic (Table 14.2). If unexpected lung, mediastinal, or pericardial pathology is found, the procedure is ideally suited to perform biopsies.

Modern thoracoscopy is not only conducted under general anesthesia and facilitated by lung isolation but can also be performed under local anesthesia and intravenous sedation with the patient breathing spontaneously. Pleuroscopy utilizing a semirigid instrument similar to a bronchoscope with a flexible tip can be performed in this fashion for evaluation of pleural effusions and biopsies of the pleura (Figure 14.5) [19–21].

Table 14.2 Common indications for thoracoscopy in the diagnosis and treatment of pleural disease.

Indication	*Goal of procedure*
Pleural effusion of unclear etiology	Diagnostic/therapeutic
Suspicious pleural mass	Diagnostic/therapeutic
Pleurectomy for spontaneous pneumothorax	Therapeutic
Drainage/decortication of empyema	Diagnostic/therapeutic
Hemothorax	Diagnostic/therapeutic
Chylothorax	Diagnostic/therapeutic

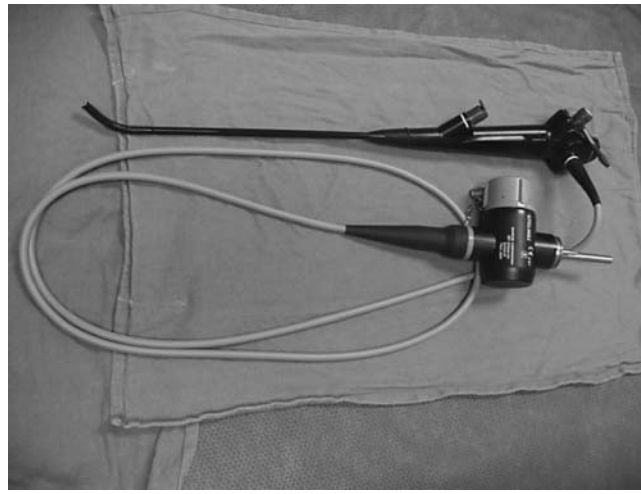


Figure 14.5 Semirigid pleuroscope (LTF160, Olympus, Tokyo, Japan).

Single-port thoracoscopy

Single-port thoracoscopy is a simple thoracic surgical technique [22]. The differences between single-port thoracoscopy and thoracentesis are summarized in Table 14.3. For the former, a single incision is made in the mid or anterior axillary line of interspace 6 or 7 (Figure 14.6). Preoperative marking (ultrasound or CT) may be required for management of complex, loculated effusions. If possible, the ipsilateral lung is deflated. The pleural space is entered judiciously to prevent parenchymal, pericardial, or diaphragmatic injury. A video mediastinoscope or a working thoracoscope is then gently inserted through the interspace. Biopsy forceps can be introduced through the working channel of the thoracoscope avoiding the need for an additional incision. When

Table 14.3 Differences between single-port thoracoscopy and percutaneous drainage in the management of pulmonary effusion of unclear etiology.

Factor	*Single-port thoracoscopy*	*Percutaneous drainage*
Cost	>$4000[a]	<$500[b]
Diagnostic accuracy	>90%	<80%
Hospital stay required	Yes	No
Evaluation of pleura	Visual inspection of pleura Site-directed tissue biopsies	Primarily cytological
Goal of procedure	Diagnostic and therapeutic	Diagnostic
Most frequent complication	Pain	Pneumothorax

[a] Estimate of Medicare reimbursement and copayment for current procedural technology (CPT) 32650.
[b] Estimate of Medicare reimbursement and copayment for CPT 32000.

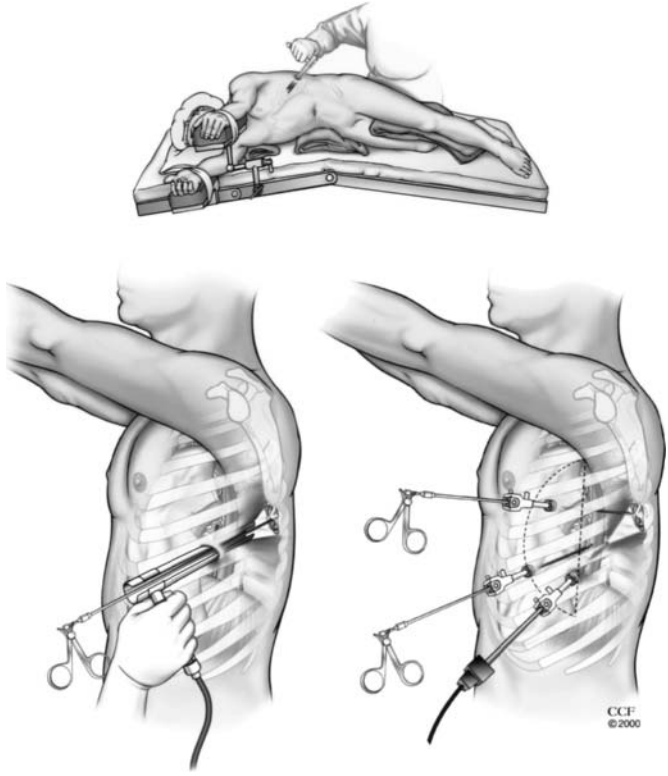


Figure 14.6 Illustration of thoracoscopy: center, standard operative position; left, single-port thoracoscopy through anterior axillary line incision; right, multiport thoracoscopy with all ports placed in the same 180° viewing arc.

bulky pleural disease is encountered (e.g. mesothelioma), the leading edge of the scope can be used to dissect the pleura from the endothoracic fascia to allow for a greater volume of tissue to be removed for diagnosis.

Multiport video thoracoscopy

Multiport video thoracoscopy is appropriate for more complex pleural operations with the use of a standard 5–10-mm magnifying videoscope with either a 0° or 30° lens. Commonly, three to four thoracoports are utilized (Figure 14.6), and two video towers are needed to allow both surgeon and assistant adequate visualization. The camera is usually introduced at interspace 6 or 7, in the mid or anterior axillary line, through a 10- or 12-mm port. Thoracoports placed in the same 180° arc reduce optical parallax problems (Figure 14.6). Ipsilateral lung isolation and thorough deflation are critical to the safety of the procedure, although simple procedures can be accomplished with brief periods of apnea or even under local anesthesia and intravenous

sedation [23, 24]. A digital survey of the chest cavity at the initial port site identifies lung adhesions and diaphragm. Once the videoscope is safely positioned in the pleural space, other ports can be strategically placed with video assistance. Appreciation of the complications associated with thoracoscopy, familiarity with the procedure, avoidance of impatience, and prudent patient selection facilitate the safe performance of the procedure [25].

Local complications include hematoma, superficial infection, rib fracture, neuralgia, and tumor seeding. Standard sterile surgical techniques and gentle handling of the chest wall tissues reduce local complications. An interspace large enough to allow passage of the scope or video port reduces soft tissue and rib trauma and decreases postoperative pain. The operating table may be slightly flexed and the patient buoyed off the table with pillows or a rigid beanbag placed under the contralateral flank (Figure 14.6). Unless the pathology mandates a posterior approach, the wider anterior interspaces should be used for large trocar or scope placement. The latissimus dorsi is avoided by a more anterior port placement. The surgeon must also be mindful of excessive torque applied on the ribs at the access site. Creation of a second port, with a more favorable viewing angle, may decrease neuralgia and reduce postoperative pain. In addition, once the thoracoscope is in place, the thoracoport can be retracted out of the chest wall onto the barrel of the scope to increase the range of motion with less torque and pressure on the intercostal nerve. Smaller operating videoscopes result in smaller and less painful incisions. Wound infection rates, though poorly documented in most reviews, should be less than 3%. In addition to tissue trauma and hematoma, it is possible that soilage of the incision with talc during pleurodesis for a malignant effusion increases the risk of port site infection. We thoroughly irrigate the port site prior to closure and occasionally tunnel the chest tube through a separate stab if the port site is macerated.

Port site recurrence rates as high as 4% due to tumor seeding have been observed with mesothelioma [26], but seldom encountered in cases of metastatic cancers to the pleura. Resection of the biopsy tract is recommended if extrapleura pneumonectomy is performed. Some surgeons advocate prophylactic radiotherapy (20 Gy) to each port following thoracoscopy for malignant mesothelioma [26].

Hemothorax and empyema complicate 1% of procedures [27]. Though considered to be a risk for empyema, thoracoscopy with talc poudrage is used to treat recalcitrant pleural space infections [28]. Prolonged air leak and subcutaneous emphysema (2% incidence of each) are secondary to direct pulmonary parenchymal injury. This often occurs during port placement when adherent lung is present at the entry site. An associated incomplete thoracoscopic decortication restricts lung reexpansion and chest wall apposition. If any concerns exist regarding incomplete expansion after a thoracoscopic decortication, a utility incision should be made and the decortication completed (Figure 14.7). Esophageal, phrenic and recurrent nerve, diaphragmatic,

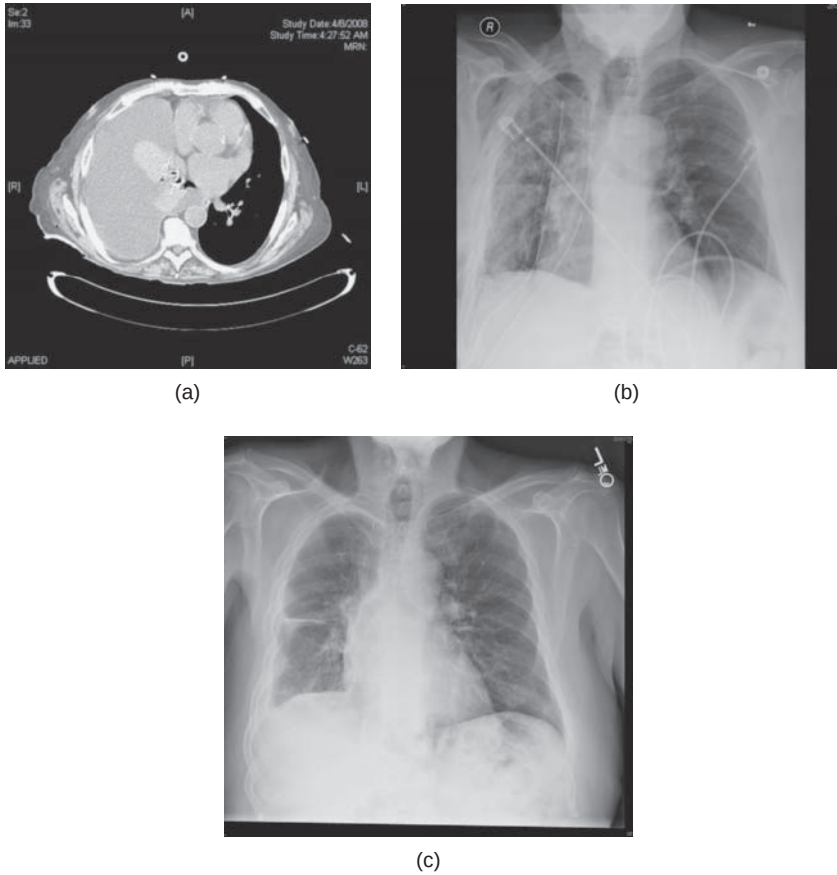


Figure 14.7 (a) Computed tomography of patient with chronic hydrothorax. Note large pleural effusion with complete collapse of entire right lung. (b) Chest x-ray following decortication of entire right lung. Note mild reexpansion pulmonary edema. (c) Resolution of reexpansion pulmonary edema and excellent lung expansion.

and cardiac injuries have been reported, and are attributable to the difficulty of appreciating anatomic boundaries in an operative field shrouded with blood, pus, or tumor. If any question of safety arises, it is advisable to convert to an open procedure.

Multiport thoracoscopy has four times the complication rate of single-port thoracoscopy [25]. Most of the increased risk is secondary to the more complex nature of most video-assisted procedures. However, in single-port thoracoscopy, there is no optical dissociation between the operator and operative field to confuse matters. Lung isolation for video thoracoscopy is often accompanied by extreme changes in arterial blood gas values. Close cooperation with the anesthesiologist expedites the procedure and reduces the incidence

of complications. The decision to employ multiport video thoracoscopy must be tailored to the goals of the procedure, the fitness of the patient, and skill of the operator.

Thoracoscopy for malignant pleural effusion

Single-port thoracoscopy is ideally suited to management of malignant pleural effusion. Cost of the procedure is significantly greater than thoracentesis (Table 14.3); however, as a diagnostic and therapeutic intervention, it has no percutaneous equal. Talc poudrage instilling 5 g of talc through the thoracoscope is more than 90% effective in controlling malignant effusions and appears to be 30–50% more efficacious than either tetracycline or bleomycin instilled at the bedside [29]. Over 50% of patients are febrile after talc pleurodesis [29]. RPE, acute respiratory distress syndrome, granulomatous pneumonitis, and cerebral microembolism have been reported as rare complications of talc insufflation [29]. We often stage bilateral procedures to prevent such occurrences. If dense lung entrapment is noted at thoracoscopy, no attempt at talc insufflation is made, since lung expansion is a prerequisite for successful pleurodesis. This situation should be anticipated if a preoperative thoracentesis results in minimal improvement in the patient's respiratory status or if postthoracentesis x-ray demonstrates incomplete lung expansion. In these cases, a pleurex catheter is utilized for ambulatory management of the effusion [30]. Daily drainage during the first several weeks is recommended to decrease occurrence of unexpandable lung and optimize chances of spontaneous pleurodesis.

Thoracoscopy for empyema

An exudative effusion with a pH less than 7.2, low glucose concentration, and preponderance of neutrophils is consistent with empyema. The algorithm of managing patients with suspected empyema usually begins with tube thoracostomy. If evacuation of the pleural space is complete and the lung expands to fill the cavity, no further procedures are necessary. The chest tube may be converted to open drainage within a week. If, however, the effusion is incompletely drained or loculated, or if the lung is entrapped, alternative therapy is required. There are no randomized data to support the efficacy of fibrinolytic therapy [31, 32] and spontaneous hemothorax is an occasional complication of chemical fibrinolysis. Large effusions or multiloculated fluid collections in the presence of pneumonia are most efficiently dealt with by early thoracoscopy even without a prior thoracentesis or chest tube.

Single-port or multiport thoracoscopy is an excellent option in this situation, and may prevent thoracotomy [33, 34]. In the presence of loculated effusions, the first port should be placed directly over the loculation to drain the fluid and avoid trauma to the lung. The thoracoscope can then be introduced in the empty pocket and direct the placement of additional ports. An early empyema can frequently be drained and the lung decorticated from its

gelatinous peel through the thoracoscope. Large-bore chest tubes are then precisely placed under direct vision for optimum postoperative drainage.

If a more mature and complicated pleural space infection is found, video assistance facilitates complete drainage. In addition to the video port, two or three operating ports are placed under video guidance. Sharp dissection is frequently necessary to start the decortication, facilitated by endoscopic monopolar scissors. Thoracoscopic ring forceps and 5-mm gauze-tipped dissectors are used to develop the decortication plane. This portion of the procedure is facilitated with partial inflation of the lung. It is essential that the pleural space be completely visualized and the entire lung mobilized to prevent a residual undrained collection. Every effort should be made to prevent parenchymal injury and prolonged air leaks. The lung must completely fill the hemithorax at the conclusion of the procedure. Preoperative and postprocedure bronchoscopic toilet decreases the likelihood that mucopurulent impaction will cause poor pulmonary reexpansion after the decortication. A 20% conversion rate to thoracotomy has been reported. Delayed referral and Gram-negative organisms increase the conversion rate [35].

It is not uncommon for patients to manifests signs of sepsis or inflammatory response after the operation, presumably from cytotoxins liberated from the pleural space. Care includes broad-spectrum antibiotics, early enteral nutrition, mechanical ventilation, and vasoactive medications. Postoperative fevers are most commonly associated with persistent septic syndrome, atelectasis, or recurrent pneumonia. A chest CT scan may be needed to exclude an incompletely drained empyema. If a postoperative fluid collection is identified, percutaneous drainage is usually sufficient. The benefit of fibrinolytic agents in this setting, although attractive, has not been documented.

Thoracoscopy for hemothorax

Thoracoscopic management of hemothorax should be considered after large-bore chest tubes have failed to adequately drain the chest. Persistent bleeding mandates thoracotomy/sternotomy for control. Any coagulopathy must be corrected preoperatively [36, 37]. Best results are obtained when drainage is performed within the first 2–5 days after trauma [37]. Intrapleural fibrinolytics have also been utilized for the successful management of retained traumatic hemothorax [38, 39].

Drainage via single-port thoracoscopy is often sufficient; although in the presence of a large clotted hemothorax, an additional port may be required. Single-port thoracoscopy is perhaps most useful to evacuate clot after an open heart procedure in which the hemithorax has been an innocent reservoir for mediastinal blood. Early thoracoscopic drainage reduces the incidence of potential empyema, trapped lung, and fibrothorax. Finally, in a posttraumatic hemothorax, all efforts should be made to avoid placing a port adjacent to a rib fracture as the injury may be worsened by scope trauma. In the absence of an obvious bleeding source, intercostal pedicle ligation at the sites of fractures should be considered as prophylaxis against recurrent bleeding. In the

subacute or chronic setting, the lung may need to be decorticated to achieve full reexpansion.

Unexpandable lung and trapped lung

Failure of the lung to expand and completely fill the thoracic cavity is not uncommonly encountered after pleural drainage procedures. The condition may manifest itself by the development of chest pain during thoracentesis or the inability to fully reexpand the lung after thoracentesis, or by a persistent pneumothorax, with or without air leak, after tube thoracostomy or placement of a pleurex catheter [40–46].

For trapped lung to develop, a pleural effusion must persist while a fibrinous peel over the visceral pleural surface organizes and develops into a fibrous membrane or peel. Once this membrane has developed, spontaneous resolution cannot be expected. Trapped lung manifests as a chronic, stable pleural effusion and may be asymptomatic or associated with restrictive physiology and dyspnea. Although most cases are diagnosed readily and are associated with infection or malignancy, in a small number of patients, the cause of the effusion remains unclear and appears to be associated with visceral pleural restriction in the presence (unexpandable lung) or absence (trapped lung) of active inflammation or malignancy (Table 14.4). Reversibility and full lung expansion is possible with medical therapy in cases of unexpandable lung (parapneumonic effusions, empyema), while decortication is required for symptomatic trapped lung. Trapped lung is a diagnosis of exclusion, and care must be taken that persisting inflammatory conditions or malignancy are not present. The most common conditions associated with trapped lung are previous cardiac surgery, uremia, thoracic radiation, pericardiotomy, repeated thoracentesis, chronic retained hemothorax, and complicated parapneumonic effusions. Pleural manometry and air-contrast CT may help establish the diagnosis [41]. Early definitive drainage of the pleural space in conjunction with therapy for the underlying condition may reduce the incidence of unexpandable or trapped lung. Asymptomatic trapped lung does not require treatment and patients should be reassured of the benign course once active inflammatory processes or malignancy are ruled out.

Table 14.4 Causes of trapped lung.

Coronary artery bypass grafting
Postcardiac injury syndrome
Complicated parapneumonic effusion
Empyema
Uremic pleuritis
Retained hemothorax
Rheumatoid pleurisy
Tuberculous pleuritis
Malignant effusions

Thoracotomy for pleural disease

With the advent of efficacious antituberculous therapy, a debilitating and painful thoracoplasty for tuberculosis is seldom necessary. On the rare occasion that the pleural space needs to be reduced or collapsed, soft tissue transfer (e.g. rotational muscle flaps, omentum, etc.) is more effective, less painful and debilitating, and cosmetically more appealing. Thoracotomy is necessary for trapped lung, dense fibrothorax, mature empyema, mesothelioma and rarely extrapleural pneumonectomy for malignant pleural seeding of thymoma or germ cell tumors of the mediastinum.

Thoracotomy for fibrothorax and mature empyema

Fibrothorax and mature empyema are two uncommon indications for thoracotomy. The procedure of choice for both conditions is pleurectomy/decortication. Since these are benign conditions, the durability of the surgery must be substantially longer than that for malignant mesothelioma. Though many of the technical nuances are the same, a few points are worth noting.

Fibrothorax represents the most severe form of pleural fibrosis and implies dense fibrosis of the visceral pleura leading to fusion of both the visceral and parietal membranes [47]. As a result, there is contracture of the involved hemithorax and reduced mobility of the lung and thoracic cage due to progressive pleural fibrosis and symphysis of the pleural space. The causes of fibrothorax are similar to those that cause trapped lung and include chronic retained hemothorax, chronic empyema, and tuberculous empyema. The differential diagnosis includes desmoplastic malignant mesothelioma. For patients with severe respiratory compromise, decortication is the only effective treatment. Since pleural thickening in these conditions typically resolves over several months, only when pleural fibrosis has been stable or progressive over a 6-month period should decortication be considered in the symptomatic patient.

Fibrothorax with lung entrapment is often more severe in the lower chest. Frequently, the diaphragm is also entrapped in the process. Parietal pleurectomy is as important as the decortication, since chest wall and diaphragmatic compliance are restored with the pleurectomy. When considering a patient for surgery, recognizing existing pulmonary hypertension alerts the surgeon to the risk of significant intraoperative blood loss.

Mature or chronic empyema is an insidious disease that manifests with constitutional, rather than local symptoms. Prior history of respiratory tract infection, low-grade fevers, night sweats, and fatigue characterize the disease. If accompanied by pleuritic chest pain and a complex fluid collection is found on chest x-ray or CT scan, chronic empyema is the most likely diagnosis. In these cases, a chest CT scan usually demonstrates a complex effusion with ring enhancement. With a mature empyema, it is prudent to proceed directly to thoracotomy since thoracoscopy is unlikely to be feasible. If encountered,

parenchymal abscesses should be widely debrided and, if small, can be left to drain into the pleural space. Visceral pleural defects should be sutured to prevent development of persistent alveolo-pleural fistulae. Fissures should be explored for entrapped fluid collections. Complete drainage of the pleural space must be achieved. Hemostasis of the denuded parietal and visceral surfaces must be achieved to prevent postoperative hemothorax. Argon plasma coagulation is ideally suited for this following temporary packing of the chest to tamponade bleeding sites.

Surgery for mesothelioma

Often, the surgeon's role is restricted to tissue acquisition for diagnosis. Single-port thoracoscopy is the procedure of choice. A common clinical scenario is the patient with asbestos and tobacco exposures who presents with an effusion or diffuse pleural disease in the absence of a dominant pulmonary mass. Fine-needle aspiration is frequently nondiagnostic or yields a diagnosis of suspected epithelioid malignancy. Thoracoscopy allows evaluation of the pleural space, generous biopsy of the pleura (to allow differentiation of mesothelioma from metastatic adenocarcinomas), drainage of the effusion, and talc poudrage, if necessary. Rarely, the procedure is extended to a minithoracotomy for tumors with a predominantly desmoplastic component, in which the biopsy specimen consists mostly of benign fibrous tissue. It is critical that enough diagnostic tissue is obtained prior to concluding the procedure.

Benign localized mesothelioma

The prognosis for benign localized mesothelioma (pleural fibroma, solitary fibrous tumor of the pleura, fibrous mesothelioma) is favorable. Preoperative chest CT scan usually demonstrates a well-circumscribed pleural-based mass with some degree of pulmonary collapse. The differential includes primary lung cancer, solitary pleural metastasis, primary sarcoma of the chest wall, bronchogenic cyst, neurogenic tumor, rounded atelectasis/pneumonia, loculated empyema, and diaphragmatic hernia. This tumor has no documented link to asbestos exposure. Curiously, unique extrathoracic manifestations (pulmonary osteoarthropathy, fever, hypoglycemia) are found in one-third of patients [48]. Surgical therapy is straightforward and can be achieved thoracoscopically (Figure 14.8). Unless resection is incomplete, surgery is curative. Surgical therapy includes *en bloc* resection of the pleural-based mass, which usually arises from the visceral pleura. Resection should include a small wedge of lung to insure that the involved visceral pleura is resected. If mediastinal or parietal pleura is the point of origin, generous margins of normal pleura should be included in the resection. Bronchoscopy prior to extubation may be necessary to alleviate mucous impaction from chronically compressed lung.

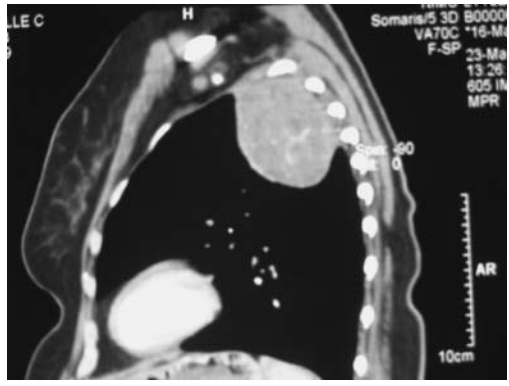


Figure 14.8 Sagital image demonstrating an apical benign fibrous tumor of the pleura. The tumor was successfully resected thoracoscopically.

Malignant pleural mesothelioma

Malignant pleural mesothelioma is a rare malignancy that arises from the mesothelium that lines the pleural cavities. Mesothelioma is usually found in patients with a history of direct or indirect asbestos exposure. The time from exposure to its clinical presentation is usually more than 20 years. Manifestations are progressive dyspnea or chest pain; malignant effusion develops in most patients. Advanced disease causes cachexia, ascites, and/or chest wall deformity. Microscopically, these tumors exhibit epithelioid, sarcomatoid, or mixed differentiation patterns. Of the three, the more common epithelioid variants have the best prognosis; the least common, pure sarcomatoid tumors, have the poorest survival. Median survival of untreated malignant mesothelioma is approximately 1 year [49].

Three different surgical approaches should be considered: talc pleurodesis, pleurectomy/decortication, and extrapleural pneumonectomy. Choice of treatment plan depends on the fitness of the patient, histology type, stage of disease, and access to skilled surgeons, radiation, and medical oncologists. Contraindications for resectional therapy because of the increased risk of postoperative complications include age more than 70 years, compromised cardiac function (ejection fraction < 45% or ischemia), pulmonary hypertension, hypercarbia (P_{CO2} < 45 mm Hg), hypoxemia (P_{O2} < 65 mm Hg), or a postresection predicted forced expiratory volume in 1 second (FEV_1) < 1 L [67]. N_2 or $T_{3–4}$ disease and mixed or sarcomatoid histology usually contraindicate resection and relegate the patient to drainage and pleurodesis of a symptomatic effusion.

Pleurectomy/decortication for mesothelioma

Indications for pleurectomy/decortication in the management of malignant pleural mesothelioma are shrinking, as trimodality therapy with extrapleural pneumonectomy gains acceptance. Initial optimism to incorporate

pleurectomy/decortication into multimodality protocols for mesothelioma has subsided, after recent trials revealed a 60% local failure rate [50]. Yet, in an otherwise fit patient unsuitable for extrapleural pneumonectomy, pleurectomy/decortication remains an option for lung entrapment.

Incision is usually made through the fifth interspace. Resection of part of the sixth rib facilitates entrance into the endothoracic fascial plane. Some surgeons utilize a second intercostal entry at the seventh interspace to simplify the dissection on the diaphragm. The parietal pleural is bluntly separated from the fascia. Points of dense adherence usually connote reactive desmoplasia or periosteal and rib involvement. Cautery or sharp dissection can be used to disconnect the pleura in these regions. Intraoperative blood loss can be minimized by serially packing the chest with laparotomy pads as the parietal pleura is mobilized. Gradually, the parietal pleura is separated from the chest wall. Intercostal pedicle avulsion indicates a deep plane of dissection. Sharp dissection is necessary to regain the proper plane. At the apex of the hemithorax, great care must be taken when detaching the pleura from the subclavian vessels. Anteromedially, careful dissection to avoid internal mammary artery injury is important as this is difficult to control if injured. Posteromedially, esophageal, azygos, or aortic perforation can be catastrophic. An injury to the phrenic pedicle anywhere along its course may negate the benefit of the procedure, as will diaphragmatic avulsion. A small amount of gross tumor left in these regions may be warranted to prevent an intraoperative calamity or postoperative disability.

After the parietal pleura has been mobilized, the tumor is incised sharply at a convenient location and the visceral pleura decorticated. Raw parenchyma can be exposed when visceral pleura is peeled away along with the tumor. As long as the lung injury remains superficial, this is of little concern. Bleeding from both parenchymal and chest wall sources is easily controlled with direct pressure, electrocautery, or argon beam coagulation. Care must be taken when decorticating the fissures as they can be inadvertently followed into the pulmonary artery. After the tumor peel is removed, the air leak may be imposing; however, as long as the lung inflates to fill the hemithorax, resolution of the air leak is surprisingly quick. Large parenchymal rents should be plicated to reduce healing time and shorten hospital stay. Two to three large-bore chest tubes are usually necessary to keep the hemithorax drained during the early recovery period. A preoperative epidural catheter is important for early ambulation and pulmonary toilet. Most patients are kept intubated and ventilated on the first postoperative night to promote lung expansion. If the air leak is manageable, chest tubes are placed on high suction to evacuate fluid from the pleural space. Positive end-expiratory pressure is applied to tamponade parenchymal chest wall bleeding. We do not advocate the routine use of postoperative adjuvant radiotherapy. The amount of radiation that can be administered to the hemithorax is limited by the radiation intolerance of normal lung and, even when the radiation planning has been meticulous, significant radiation pneumonitis results [50, 51]. Unfortunately, most patients

recur within 1 year. Currently, no proven salvage therapy exists for recurrence [51–53].

Extrapleural pneumonectony for mesothelioma

The technical challenge of this resection is matched equally by the diligence and experience required to recover patients postoperatively [49, 54, 55]. In 1976, the initial operative mortality was reported at 30% [56]; today, a 30-day mortality of more than 5% is excessive [54]. This procedure is not restricted to mesothelioma. Pleural sarcoma and advanced, refractory tuberculosis disease may also require extrapleural pneumonectomy.

Since malignant mesothelioma is a locally aggressive disease, the more complete the resection, the better the outcome explaining the markedly lower local recurrence rate after resection compared with pleurectomy/decortication [57]. Local control is enhanced by adjuvant radiotherapy to the empty hemithorax. Patients who benefit most from resection have early-stage, node-negative, epithelioid tumors [55, 58]. Extrapleural pneumonectomy for mesothelioma should be reserved for patients enrolled in a trimodality protocol.

Extrapleural pneumonectomy encompasses the pleural envelope with lung, diaphragm, pericardium, and a complete lymphadenectomy. Difficulties encountered during the resection are identified in Figure 14.9. Resection of all gross disease is the goal, as benefit from the procedure has only been demonstrated with negative resection margins [58]. Involvement of the ribs, mediastinum, esophagus, aorta, or subclavian vessels contraindicates resection. This should be investigated preoperatively by MRI scanning [2]. If transpericardial or transdiaphragmatic spread is found, the resection should

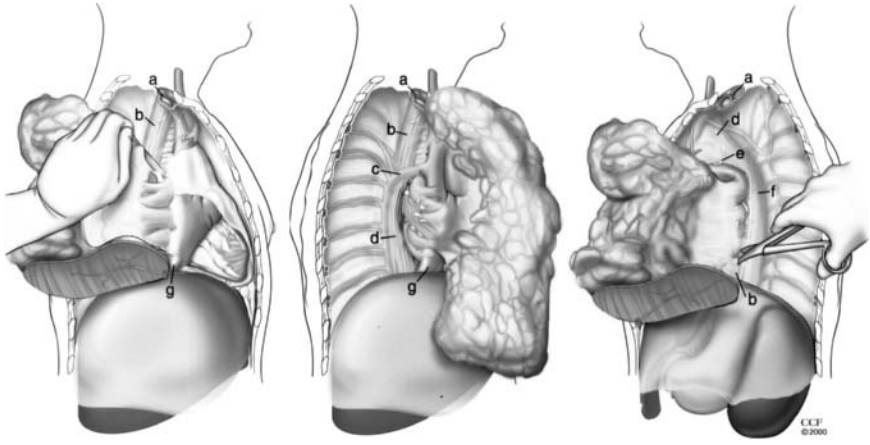


Figure 14.9 Depending upon the side of the malignant mesothelioma, several anatomic structures must be protected during extrapleural pneumonectomy. (a) Subclavian vessels. (b) Esophagus. (c) Aazygous vein. (d) Vagus nerve. (e) Left recurrent nerve. (f) Aorta. (g) IVC. Injury to any of these structures will result in intraoperative difficulty and postoperative morbidity.

be aborted. Limiting the number of intraoperative surprises facilitates a safe and beneficial outcome.

As with pleurectomy, much of the dissection is done bluntly, hemostasis is obtained by direct pressure. If the proper extrapleural plane is developed, the dissection proceeds smoothly. In the case of a frozen hemithorax, the sixth rib may be sacrificed to allow access to the endothoracic fascial plane, although rib resection makes chest closure significantly more difficult. Using a sponge-stick and sharp dissection, it is possible to mobilize the superior sulcus from the subclavian vessels, stellate ganglia, esophagus, and vagus nerve. A nasogastric tube permits intraoperative identification of the esophagus. In very early-stage disease, with low tumor burden, dissection is frequently more tedious as the pleura is not thickened. In these cases, islands of normal-appearing, thin, parietal pleura often separate from the specimen and remain attached to the chest wall. A piecemeal approach must be adopted to finish the resection.

Diaphragmatic and pericardial resections are undertaken only after it is certain that the resection can be completed. The diaphragm is mobilized bluntly, beginning from the costovertebral sulcus. Much of this dissection is done blindly, with fingers being interdigitated between slips of diaphragm muscle (a "bunk-bed" thoracotomy may simplify this aspect). This sulcus is a difficult area to visualize and a common site for gross disease to be left behind. Once the diaphragm has been partially disconnected, the specimen can be rolled into view, the lateral aspect of the diaphragm incised with cautery and bluntly separated from underlying peritoneum.

As the diaphragm is resected, the peritoneum is frequently adherent to the underside of the central tendon. Defects are oversewn to reduce the chance of ascites developing as the chest fills with pleural fluid and to decrease the risk of peritoneal implants migrating from residual pleural disease. Posteromedially toward the crus, inferior phrenic pedicles need to be effectively controlled. For right-sided resections, disconnection of the diaphragm at the level of the inferior vena cava is done after the pericardium has been opened anteriorly with continuation posterior to the cava. The specimen is removed when the posterior pericardium is cut with intrapericardial division of the pulmonary veins and pulmonary artery and stapling of the bronchus. It is surprisingly easy to tent the esophagus up into the field while detaching the specimen from the posterior pericardium. The procedure is concluded with Gortex patch reconstruction of the diaphragm and pericardium for right-sided procedures and soft tissue coverage of the bronchial stump is recommended (Figure 14.10) [55].

In a procedure of this magnitude, even small technical complications can be catastrophic. Table 14.5 summarizes complications observed after extrapleural pneumonectomy. Cognizance of the technical subtleties of the procedure promotes a more uneventful postoperative course.

During the recovery period, pulmonary edema, mediastinal shift, atrial arrhythmia, vocal cord palsy, and pain contribute to respiratory insufficiency.

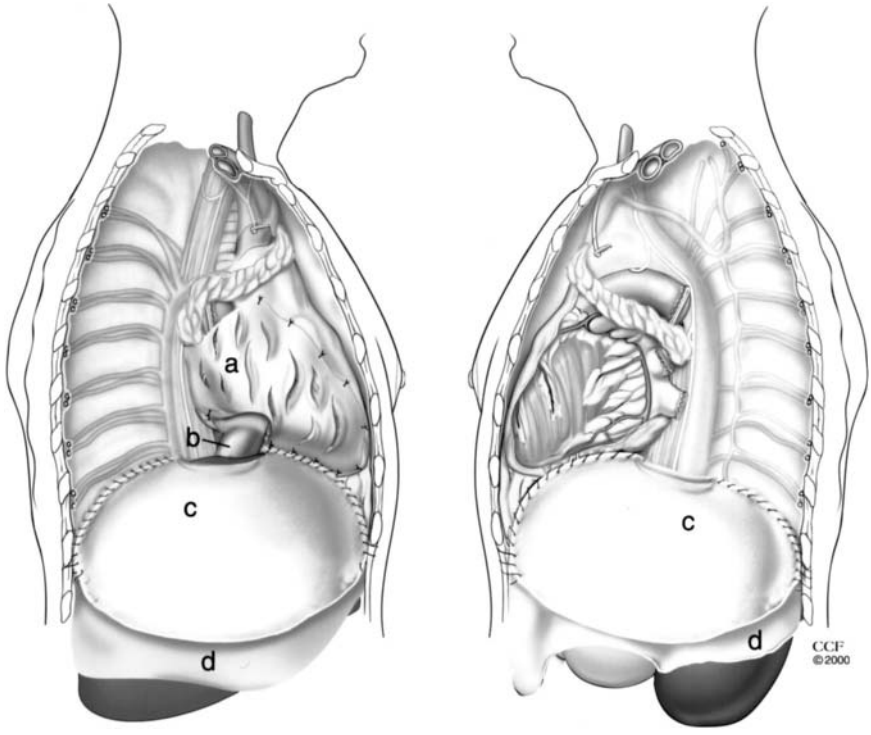


Figure 14.10 After the surgical specimen has been removed during extrapleural pneumonectomy, postoperative complications may result from improper reconstruction and closure. Specific sites include (a) pericardial patch disruption leading to cardiac herniation or a tight patch resulting in tamponade; (b) IVC entrapment by either pericardial or diaphragm patches; (c) dehiscence of the diaphragm patch and abdominal herniation; (d) unsuspected hemorrhage below the reconstructed diaphragm. Bronchial stumps should be covered (the thymic fat pad is illustrated).

In addition to effective pain management and early ambulation, gentle diuresis, balancing of the mediastinum, and vocal cord injection to restore a functional cough may be necessary. Most diaphragmatic patch problems manifest within the first week, if not the first day, and mandate an immediate return to the operating room. Chest x-ray demonstrates a left-sided diaphragm patch dehiscence as the gastric air bubble ascends into the left chest. A right-sided diaphragm patch disruption may be more insidious. The liver is still partially fixed to the peritoneal cavity laterally and posteriorly after resection, and may not swiftly fill the cavity if the reconstruction fails. If the liver herniates into the right chest, the chest x-ray may not change appreciably. Often, an ultrasound or chest CT is required to diagnose the problem. Dehiscence of the right-sided pericardial patch usually results in ventricular tachycardia followed promptly by fibrillatory arrest. When the heart herniates into the pneumonectomy space, venous return is severely comprised as both

Table 14.5 Observed postoperative complications following extrapleural pneumonectomy.

Complication	*Possible cause*
Hypotension	
Falling HCT	Bleeding ± coagulopathy
Stable HCT	Epidural analgesia ± ipsilateral sympathetic chain injury
	Hypovolemia secondary to early fill-up
	Myocardial ischemia
	Atrial arrhythmia
	Right-sided Gortex patch compressing IVC
	Sepsis from occult esophageal injury
Hoarseness/weak cough	Left recurrent nerve injury
Respiratory insufficiency	Postpneumonectomy pulmonary edema
	Mediastinal shift from rapid fill-up
	Aspiration
Ventricular arrhythmia	Myocardial ischemia
	Pericardial/diaphragm patch disruption and cardiac malrotation or entrapment
Dysphagia	Submucosal esophageal hematoma
	Vagal injury
Incisional seroma	Improper chest closure and extravasation of fluid from chest
Contralateral pleural effusion	Contralateral parietal pleura injury during the procedure

inferior and superior vena cavae become occluded. If this happens, the patient should be immediately placed in a left-lateral decubitus position, to drop the heart back into the pericardial cavity, and returned to the operating room. Cardiac compressions, if necessary, should be done open. If the pericardial patch is too tight, a tamponade-like syndrome is created. It is important to reef or fenestrate the pericardial patch to permit ample laxity (Figure 14.10).

The extrapleural dissection induces rapid filling of the hemithorax. Often, the fluid level is above the carina on the first postoperative day, before the thoracotomy has sealed. Meticulous suture closure of the thoracotomy is critical. If a rib was resected, serratus anterior mobilization and coverage may be required. The closure should be watertight to lessen the risk of a superficial seroma in free communication with the intrathoracic space. Should this occur, a compressive chest wrap can be employed at the expense of pulmonary restriction. The skin incision must be kept intact to prevent seeding of the chest cavity by skin flora.

Regardless of mechanism, the development of empyema following extrapleural pneumonectomy is a challenging problem. Infection is complicated by patch material in the field and is not amenable to catheter-based, percutaneous, antibiotic irrigation protocols. As with a postpneumonectomy empyema, patients are lethargic and fatigue easily. Low-grade fevers are common, but very little else localizes the infection to the chest. A sterile thoracentesis is reassuring but does not rule out the diagnosis. Open drainage after debridement of the chest cavity and removal of the patch material is

recommended. The diaphragm can be reconstructed with vicryl mesh and allowed to granulate. For empyema following a right-sided resection, the pericardial patch may be replaced by bovine pericardium, autologous fascia lata, or ipsilateral parietal pleura [59], and the cavity managed with dressing changes. A more conservative approach of closed antibiotic irrigation can be considered in the absence of a bronchial stump problem. Removal of infected tissue and the patch(es) at rethoracotomy is a prerequisite. This postoperative complication usually prevents the patient from receiving adjuvant therapy, compromising the benefits of the surgery.

Residual postoperative pleural space

A residual postresectional pleural space develops in up to 10% of patients undergoing pulmonary resections for lung cancer [60, 61]. It is more common after upper lobectomy and, in the absence of associated bronchopleural fistula or prolonged air leak, has a favorable outcome. Reduction of the pleural space can be achieved by pleural tenting, pneumoperitoneum or through controlled paralysis of the diaphragm by continuous paraphrenic infusion of lidocaine or bupivacaine [62–63].

Pleural space complications after pneumonectomy

The overall incidence of complications after pneumonectomy is as high as 20–60%, although the associated morbidity and mortality have decreased in recent decades [64–70]. The nature of these complications differs according to the length of time between pneumonectomy and the onset of the complication.

Familiarity with the fate of the pneumonectomy space is required for timely identification of complications. At the conclusion of the pneumonectomy, the mediastinum is repositioned in the midline by evacuating 700–1000 mL of air with the chest closed. Within the first 4–5 postoperative days, approximately half of the pneumonectomy space is filled with fluid, with the mediastinum in the midline or slightly deviated to the operated side. The air–fluid level subsequently gradually rises and the mediastinum either remains stationary or gradually shifts toward the postpneumonectomy space. Total obliteration of the postpneumonectomy space usually takes weeks to months. In the immediate postoperative period, a rapid mediastinal shift toward the remaining lung indicates atelectasis or abnormal accumulation of fluid or air in the postpneumonectomy space. Volume-expanding complications after pneumonectomy result from a bronchopleural fistula, hemorrhage, chylothorax, or empyema [71, 72]. In the late postoperative period, mediastinal shift toward the remaining lung is indicative of a delayed complication in the pneumonectomy space.

Early postpneumonectomy complications

The incidence of empyema after pneumonectomy varies between 0.8% and 15%, with most series citing an incidence of less than 5% [73–78]. Empyema is a potentially fatal complication and can appear early or months to years

after pneumonectomy. Empyema in the early postoperative period is attributed to intraoperative contamination of the pleural space. Factors associated with increased risk include completion pneumonectomy, pneumonectomy for benign disease, right pneumonectomy, preoperative radiation or chemotherapy, gross contamination of the pleura, long bronchial stump, extensive mediastinal node dissection, amount of blood transfusion required, low FEV_1, and diffusing capacity and postoperative mechanical ventilation. It may or may not be associated with a bronchopleural fistula.

At the time of pneumonectomy, the bronchial stump should be treated with extreme respect, avoiding devascularization and excessive length. Bronchial stump closure with staples may have a protective effect against bronchopleural fistula compared with suture closure [73]. If the mediastinum and hilar area have been irradiated prior to pneumonectomy, reinforcement of the closed bronchial stump with a muscle or pericardial flap reduces dehiscence [73]. Other indications for prophylactic protection of the bronchial stump include operating in the presence of empyema or destroyed lung [73]. Every effort should be made to prevent hemothorax or chylothorax in the pneumonectomy space. Aprotinin has been associated with decreased use of nonpacked red blood cell products and lower postoperative chest tube output in patients undergoing extrapleural pneumonectomy [79]. Prophylactic intracavitary antibiotic instillation in the pneumonectomy space and early chest tube removal have been associated with a decreased incidence of postpneumonectomy empyema [80].

Treatment of postpneumonectomy empyema must also address the bronchopleural fistula if present. In the absence of a bronchopleural fistula, postpneumonectomy empyema can be treated in one of several ways: open thoracostomy (Eloesser window) with frequent dressing changes, repeated open surgical debridement with negative pressure wound therapy (wound-vac), repeated thoracoscopic debridement with or without continuous antibiotic irrigation, and tube thoracostomy with intrapleural instillation of fibrinolytics and antibiotics [73, 77, 78, 81–84]. In the presence of a bronchopleural fistula, a modified Claggett procedure is recommended [73].

Cardiac herniation is a very rare complication. Mortality reaches 50% in recognized cases and 100% in undiagnosed cases [85]. Herniation is the result of prolapse of the heart through the pericardial defect created during surgery for mesothelioma or during intrapericardial pneumonectomy and is most common after a right pneumonectomy [85–88]. Patients typically manifest sudden hypotension, cyanosis, and respiratory distress as kinking or torsion of both vena cavas reduces cardiac filling. On the left side, cardiac herniation can also cause dysrythmias and myocardial ischemia by compression or strangulation of the ventricular wall by the pericardial edges [85–88]. Positioning of the patient with the operative side dependent and immediate return to the operating room are mandatory for survival. Delayed cardiac herniation has also been described [88]. Cardiac herniation can occur after primary closure of the pericardium [86]. Prevention of this complication involves repairing even small

defects of the pericardium with prosthetic material and interrupted mattress sutures.

Chylothorax

Chylothorax may occur following several surgical procedures including esophagectomy and pulmonary resections. At the time of surgery, every effort should be made to control the leak if clear fluid is identified seeping from the dissected planes. Direct suture ligation with pledgets or judicious application of clips may be performed with care to include surrounding tissue as attempts to isolate and include only the lymphatic channel usually results in tearing and failure. Ligation of the thoracic duct just above the diaphragm may be performed when operating on the right hemithorax. A chylous effusion that is diagnosed in the postoperative period may be treated in a number of ways depending on the etiology and output. Options include adequate drainage and absolute diet (NPO), octreotide, medium chain triglyceride diet, and thoracic duct ligation or embolization with coils [89, 90]. Percutaneous embolization is an effective technique, may obviate reoperation, and should be considered the procedure of choice in large output chylothorax.

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CHAPTER 15

Complications from Chest Wall Procedures

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Chest wall resections are performed for a variety of reasons, including removal of primary or metastatic cancers, removal of tumors that grow into the chest wall from adjacent organs, and treatment of infections or radionecrosis of the chest wall. The purpose of this chapter is to describe the complications that occur from these chest wall procedures and explain the potential management options.

Occasionally, the bony chest wall does not need to be reconstructed, especially when the defect is small (<3 cm) or it will be covered by the scapula. However, if a defect is under the inferior edge of the scapula, the tip of the scapula can catch on the inferior edge of the chest wall defect, and this will lead to a chronic clicking and discomfort. A bursa can develop in this area and be quite disabling for the patient. Therefore, if there is any chance that the tip of the scapula will hit on the inferior aspect of a chest wall resection, that is an indication for some sort of bony coverage, usually with prosthetic mesh, to prevent the scapula from hitting on the inferior aspect of the defect (Figure 15.1a–c).

Wound infection

The most frequent complication after chest wall resection and reconstruction is an infection. Not only this complication is much more problematic when prosthetic material has been used to reconstruct the bony chest wall, but it can also occur after a reconstruction that does not involve prosthetic material. Infection may occur because of the patient's debilitated state, from contamination from surrounding tissue, such as resected lung, or because the tissue is of poor quality as in the case after radiation therapy. Staphylococcus aureus and streptococcus are the most common organisms, although almost all organisms have been reported to be involved in these types of infection. The signs and symptoms can sometimes be difficult to detect, although occasionally gross

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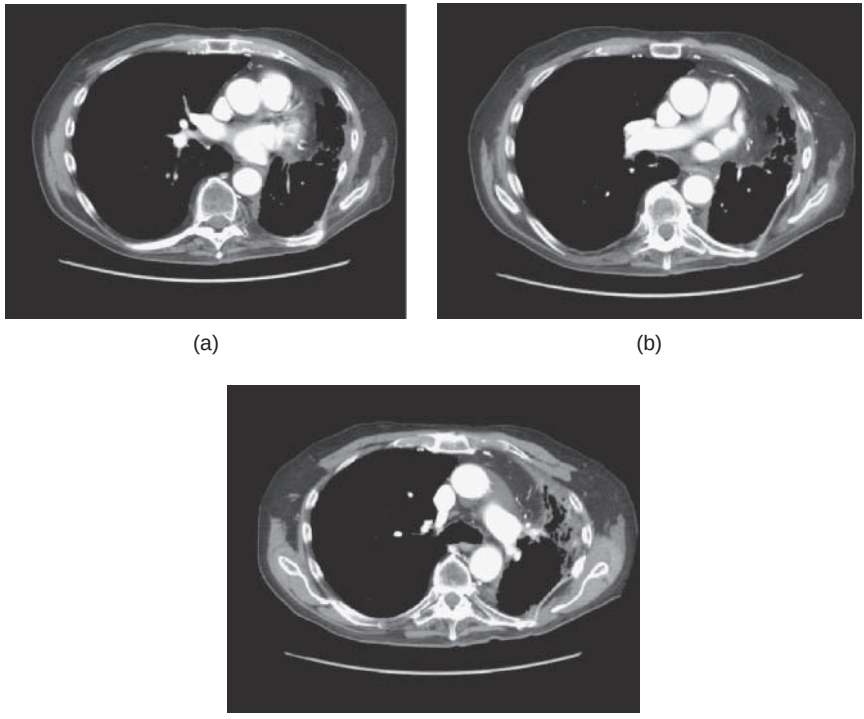
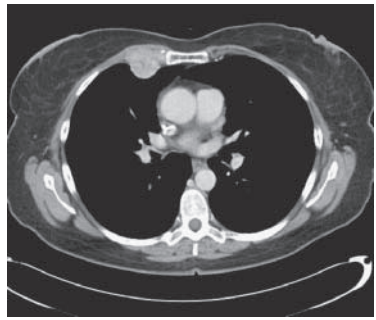


Figure 15.1 (a–c) Gore-Tex reconstruction to prevent tip of scapulae from hitting the rib cage.

purulence can be seen draining from the incision and the diagnosis is simple. More difficult are infections that are deep underneath multiple layers of soft tissue and muscle and are hidden and only present as a fever of unknown origin, leukocytosis, or increased pain in the area of the resection. The diagnosis frequently can be obtained by physical examination and expressing purulent material from the incision. If the physical exam is not diagnostic, a CT scan is appropriate and will show a collection of fluid, and an aspiration will reveal purulent material (Figure 15.2a–e). The treatment of these types of infections is similar to other incisional infections that occur, with the important caveat that the incision can not be just open and drained because if the incision is in continuity with the pleural cavity, the lung will not stay inflated without positive-pressure ventilation. In these patients, the incision should be opened, debrided, and closed with drainage. In patients with infection and prosthetic material, this usually needs to be removed. This is the case with Gore-Tex (registered trademark of W.L. Gore and Associates, Inc., Flagstaff, AZ, USA) or methylmethacrylate. It has been reported that Marlex mesh and Vicryl mesh can be left behind even in the face of infection. When prosthetic material has to be removed, there is usually enough of a fibrous peel over the pleural space that pneumothorax does not occur. However, one should be prepared to cover



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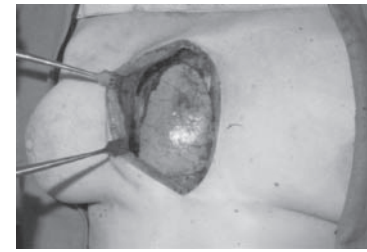

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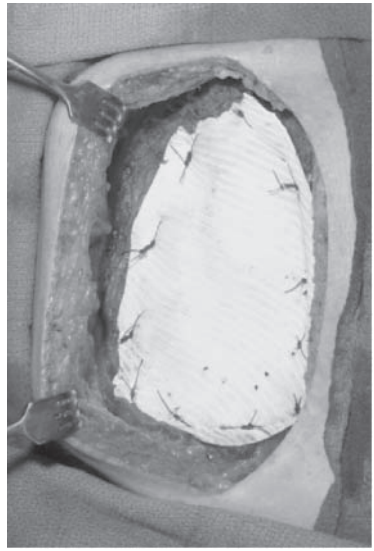

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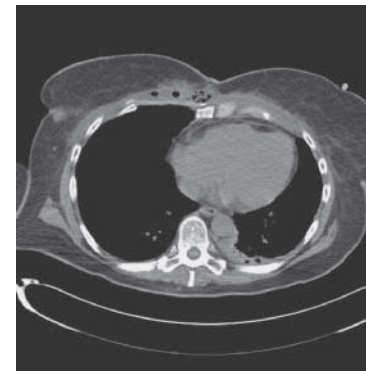

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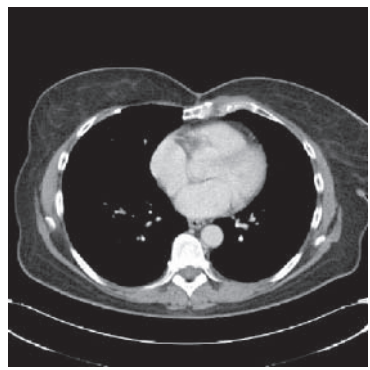


(f)

Figure 15.2 (a) Chest wall lesion on right anterior parasternal area. (b) Defect after resection of chest wall. (c) Gore-Tex patch reconstruction of the sternal defect. (d) Coverage of Gore-Tex with bilateral pectoralis advancement flaps. (e) Collection of fluid and gas over Gore-Tex patch. (f) Computed tomography of chest after Gore-Tex patch removal

the defect with viable tissue via some type of muscle flap. Once the infection has healed, there is usually enough of a fibrous scar that the cosmetic and physiologic deformity is not sufficient to require reoperation.

In the series by Deschamps *et al*., they reported a 4.6% (nine patients) incidence of wound infections after placement of prosthetic material to reconstruct a chest wall resection. In five patients, the infection occurred after reconstruction with Prolene mesh and all eventually had their mesh removed from 13 to 64 days after surgery. In all of these patients, the lung had adhered to the chest wall and no pneumothorax occurred with removal. In four patients, the infection occurred after using 2 mm polytetrafluoroethylene patch (Gore-Tex patch) for reconstruction. These wounds were managed by opening, debridement, and packing. All of these healed by secondary intention. Although the authors were able to salvage the prosthetic material in these four patients, they do not recommend using prosthetic material when resecting a contaminated wound. In the series from Emory University by Mansour *et al*., they reported a 5% (nine patients) infection rate, but do not provide detail about the management or type of reconstruction that was performed in these patients.

Respiratory failure

Another complication that occurs after chest wall resection is respiratory failure. This may be caused by excessive pain from multiple rib resections but, more importantly, it may be caused by the physiologic effect of removing the bony chest wall and interfering with the mechanics of breathing, very similar to what would occur after a flail chest. Management and prevention of respiratory failure is mostly related to excellent pain control with either epidural or local anesthesia and obtaining some sort of stability of the chest wall. Stability of the chest wall can be done with 2.0 mm polytetrafluoroethylene patch, Vicryl mesh, Marlex mesh, or Marlex–methylmethacrylate sandwich. Although respiratory failure is more common after a lung cancer operation with chest wall resection, it has never statistically been shown to be an independent predictor of postoperative pneumonia. In the series from Emory, they reported pneumonia in 27 (14%) and ARDS in 11 (6%) patients. Whether or not these were from pulmonary dysfunctions from chest wall disruption or preexisting underlying pulmonary disease is not stated. In any event, these two complications accounted for the vast majority of complications reported in their experience. In Deschamp's report, respiratory complications accounted for 24.4% (48 patients) of their morbidity. They also do not specifically describe the cause of the respiratory morbidity, but the reader may assume that at least part of it is from impairment of the respiratory mechanism after a chest wall resection. The above results serve to emphasize the need for careful preoperative pulmonary evaluation before a chest wall resection, especially if it is anticipated to be a large (i.e., >10 cm) resection. Respiratory therapy postoperatively is also very helpful in reducing the frequency and severity of this morbidity.

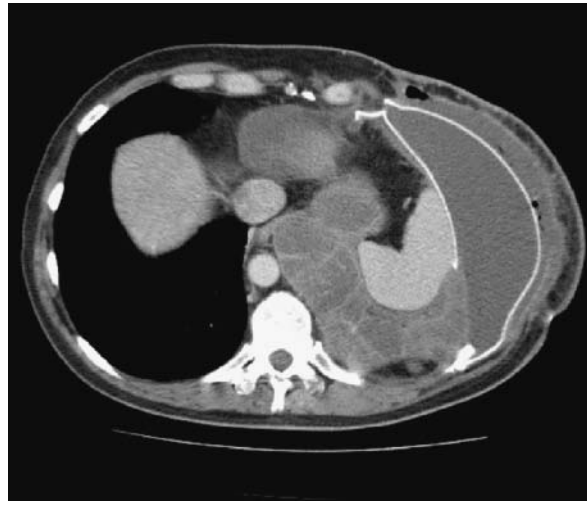
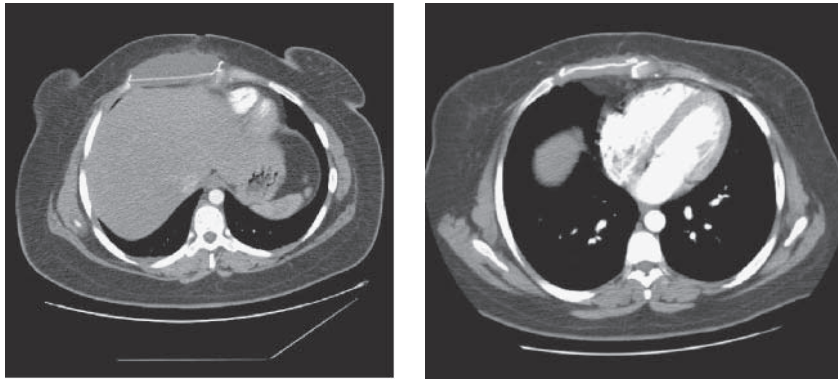


Figure 15.3 Seroma after a left chest wall resection and reconstruction with Gore-Tex.

Fluid collections

Fluid collections that are not infected can develop around a prosthetic material after chest wall resection. These typically present as a bulge with a ballotable mass near the incision (Figure 15.3). These can usually be aspirated under sterile technique until they are dry, and then some type of compression dressing is placed on the incision to try and prevent recurrence of the seroma. The pressure dressing is thought to impede accumulation of fluid by changing the pressure relationships and decreasing fluids. These fluid collections are usually responsive to this relatively simple therapy (Figure 15.4). Occasionally, they will require a long-term drain to be put in place; however, the long-term



(a) (b)

Figure 15.4 (a) Seroma over Gore-Tex. (b) Follow-up CT of the chest after aspiration of a seroma.

drain does raise the possibility that bacteria can travel up the drain and infect the prosthetic material. Wound seromas occurred in 7.1% (14 patients) in Deschamp's series. There were 10 (7.5%) after polytetrafluoroethylene reconstruction and 4 (6.2%) after Prolene mesh reconstruction. Twelve of the seromas were small and resolved, six after repeated percutaneous drainage. The remaining seromas underwent surgical exploration with obliteration of the cavity with eventual healing. Interestingly, none of these patients developed a wound infection.

Cosmetic outcomes

Unacceptable cosmetic outcome is another complication that can occur after chest wall resection. This is relatively uncommon, because it is fairly simple to get a good bony reconstruction after a resection. However, if there is a large defect, more than 20.0 cm, then the curvature of the thoracic cavity must be reestablished. This can be best done with a Marlex–methylmethacrylate sandwich shaped to match the curvature of the resected chest wall. If patients are unhappy with their cosmetic outcome, revision at a later date is always an option, once the primary tumor is under control.

Pain

Postoperative pain is another debilitating complication and occurs in both acute and chronic forms. In the acute form, relatively standard methods of treating postoperative pain can be utilized. These include epidural anesthesia, which should be started preoperatively to minimize the chances of the patient ever experiencing severe postoperative pain that reduces the likelihood of the development of chronic pain. In addition, parenteral and oral narcotics, and anti-inflammatory drugs such as Ketorolac (Toradol, Roche Laboratories, Nutley, NJ, USA) or Ibuprofen are used as needed. In a chronic setting, occasionally there is a postoperative thoracic syndrome with acute neuralgias from the cut end of the intercostal and subcutaneous nerves. These syndromes are much more difficult to manage and usually do not respond to further surgical therapy but rather are best managed by long-term analgesic methods such as injection of local anesthetic, nerve ablation, transcutaneous nerve stimulation, or low-dose transcutaneous narcotic analgesics.

Flap loss

Another complication that occurs is flap loss, something that should always be considered in planning the reconstructive options after a chest wall resection. This is most common when there is a large flap or there is an impaired vascular supply to the flap. To minimize the possibility of this complication by taking advantage of their expertise and experience, plastic surgery colleagues should be part of the reconstruction team and prepared for secondary and even tertiary options for chest wall reconstruction. In an extensive

review of the Memorial Sloan–Kettering Cancer Center's experience with reconstruction of oncologic chest wall defects by Chang *et al.*, they rarely had full flap loss. They reported that only 7 (4%) patients out of 113 that underwent reconstruction with flaps had partial flap loss. All of these patients had loss of the distal aspect of the flap. In two of the patients, critical illness developed, ultimately causing postoperative death.

Mortality

Mortality after a chest wall resection is unusual and is often caused as a result of complication from an underlying disease or a simultaneous pulmonary resection. In the Mayo series, the mortality was 4.1% and all of the mortality were in patients who had concomitant pulmonary resection at the time of chest wall resection and reconstruction. Causes of death were myocardial infarction in three patients, respiratory failure in three, pulmonary embolus in one, and multiple organ failure in one. A similar mortality rate was seen in the series from Emory University. They reported 7% mortality. Almost all of the mortality occurred in patients that had a four quarter amputation with chest wall resection or, as in the Mayo experience, with pulmonary resection. The mortality in the series from Memorial Sloan–Kettering Cancer Center was 4%.

Author	*Chang [1]*	*Mansour [2]*	*Deschamps [3]*
Institution	MMSK	Emory	Mayo
Year	1992–2002	1975–2000	1977–1992
Number of patients	113	200	197
Average age (range)	58 (19–88)	54 (13–86)	59 (11–86)
Men/women	25/88	106/94	109/88
Major indications	Breast Ca 40% Sarcoma 24% Infection 11%	1° Lung Ca 38% 1° Chest wall Ca 27% 1° Breast Ca 22% Radionecrosis 15%	Recurrent CW Ca 55% 1° Chest wall Ca 32% Adj. Lung Ca 27%
Prosthetic material used for reconstruction	Methylmethacrylate 55%	Prolene mesh 25% Marlex mesh 11% Methylmethacrylate 6%	PTFE 68% Prolene mesh 32%
Muscle flaps used	Lat. Dorsi 33% Rectus Abdom. 33% Pectoralis major 22% Free flap 17%	Lat. Dorsi 20% Pectoralis major 16% Tram 17% Free flap 9%	Not stated
Operative mortality	4%	7%	4%
Complications	Not stated	24%	46%
Pneumonia	Not stated	20%	24%
Infection	7%	5%	5%
Hematoma	3%	2%	2%
Seroma	Not stated	Not stated	7%
Flap loss	4%	5%	Not stated

These also occurred in the setting of advanced disease in patients that underwent complex resections and were not the result of flap reconstruction.

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CHAPTER 16

On-Pump Coronary Artery Bypass Grafting

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Morbidity and mortality following on-pump isolated coronary artery bypass grafting (CABG) remains low due to many modern advances in operative technique, effective cardioplegia techniques, and improved postoperative care. The Society of Thoracic Surgeons (STS) 2008 Report (encompassing all of 2008) lists an operative mortality of 2.0% (1.6% risk adjusted) and a major complication rate of 12.4% (risk adjusted) for on-pump CABG [1]. This chapter will focus on the avoidance and treatment of complications of on-pump (utilizing cardiopulmonary bypass) CABG. Other chapters will address complications related to the cardiopulmonary bypass machine, myocardial preservation, and off-pump CABG.

Preoperative evaluation

Many complications encountered during on-pump CABG may be avoided by careful preoperative assessment and planning. This assessment is extremely important, not only in planning the procedure, but also in communicating operative risk and possible alternatives to the patient.

The preoperative assessment begins with a complete history and physical examination. With the increasing use of electronic medical records, a complete summary of previous hospitalizations and significant medical issues may be reviewed. Nonetheless, the best history and physical exam is usually obtained directly from the patient with little reliance on data obtained (sometimes incorrect and repeatedly copied) in the patient's chart. Table 16.1 [2–6] highlights key historical and physical findings that may alert one to the possibility of future complications. These findings may prompt additional testing or evaluation to aid in the planning of the operative procedure.

Several preoperative assessment tools are available to determine a numerical and objective evaluation of operative risk. These tools include the *Euro*SCORE and the STS Risk Model Score [7, 8]. Both methods utilize

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Table 16.1 Pertinent findings on history and physical exam guide preoperative planning.

Key findings	*Potential importance*
Preoperative state[a,b]; unstable angina[b]; CHF[a]; shock[a]; NYHA class[a]; preop IABP[a,b]	Timing of procedure
Previous cath, recent MI[a,b]; stents; PCI; ejection fraction[a,b]; left main disease[a]	Carefully plan complete revascularization, target location, consider viability study
Pericarditis	Anticipate difficult dissection
TIA or CVA, any current symptoms[a]	↑ Risk of CVA, consider carotid Doppler, consider combined procedure
DM[a], control of DM[a]	↑ Risk wound infection [2], ↑ mortality [3]
Hypertension[a]	↑ Risk of CVA
Renal failure[a]; recent cath; baseline creatinine[a,b]	↑ Risk of renal failure [4]
COPD; emphysema; significant lung disease[a,b]; use of home oxygen; pulmonary hypertension[a,b]	Consider PFTs, ↑ risk of prolonged ventilation
Liver disease; bleeding problems; coagulation profile	Anticipate excessive bleeding, consider hematology or hepatology consult
PVD (including carotid)[a,b]; claudication; DVT	Consider vein mapping, bilateral lower extremity arterial Doppler, dictate site of conduit harvest, ↑ risk cerebrovascular accident
Neurologic dysfunction[b]	Difficult rehabilitation, ↑ risk pulmonary complications
Malignancy with chest wall XRT	Anticipate difficult dissection and friable tissues
Previous sternotomy[a,b]	Obtain previous operative note, anticipate difficult dissection, plan for possible femoral access
Previous tracheostomy	May indicate ↑ risk for ventilator dependence
Varicose vein stripping	Consider vein mapping
Allergy to heparin, protamine	Consider hematology consult, plan alternate agents
Immunosuppression or steroid use[a]	↑ Risk of poor wound healing, fragile tissues
Recent use of Plavix; antiplatelet agents; IIb–IIIa inhibitors	↑ Risk of bleeding, timing of surgery
Exercise tolerance	Good indicator of outcome
Social support	Difficult rehabilitation if poor support mechanisms
Tobacco abuse[a]; ethanol abuse; elicit drug use	↑ Risk pulmonary complications, risk of substance withdrawal
Age[a,b]; gender[a,b]; race[a]	↑Age: ↑ risk CVA, prolonged ventilation [5]; female: ↑ mortality
Abnormal (low or high) BMI[a]	↑ Risk of sternal infection or nonunion, ↑ mortality [6]
Carotid bruits	Not necessarily correlated with stenosis, consider carotid Doppler

Table 16.1 (*Continued*).

Key findings	*Potential importance*
Loud heart murmur	Identify source
Diffuse crackles on lung exam	Timing of surgery
Pulsatile abdominal mass	Consider abdominal ultrasound
Varicose veins; nonhealing ulcers; poor distal pulses; Allen test	Guide decisions regarding location of conduit harvest

BMI, body mass index; CHF, congestive heart failure; COPD, chronic obstructive pulmonary disease; CVA, cerebrovascular accident; DM, diabetes mellitus; DVT, deep venous thrombosis; IABP, intra-aortic balloon pump; MI, myocardial infarction; NYHA, New York Heart Association classification; PCI, percutaneous intervention; PFT, pulmonary function test; PVD, peripheral vascular disease; TIA, transient ischemic attack; XRT, radiation therapy.
[a]STS risk model variables.
[b]*Euro*SCORE risk factors.

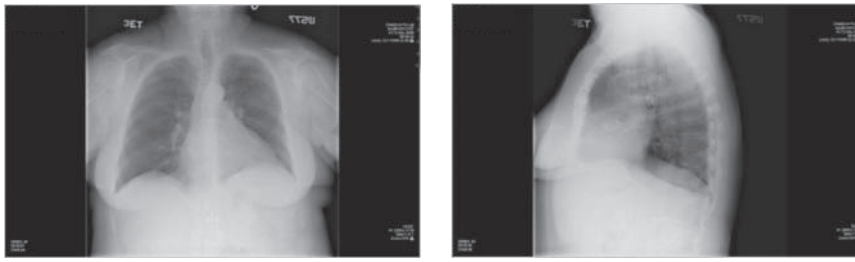
measurable factors to stratify risk. The *Euro*SCORE derives risk by totaling points for each risk factor, whereas the STS algorithm derives risk via a patented software calculation after risk factors are entered [7, 9]. Risk factors for each stratification system as they apply to on-pump CABG are noted in Table 16.1. An accurate preoperative risk assessment will aid in preoperative planning and may also indicate that the risks of an operative approach may outweigh the benefits in some cases.

Conduit selection

Operative plans for conduit use are typically determined during the initial patient evaluation. Considerations should include the patient's livelihood (upper extremity fine motor skills and manual dexterity may be vital), age (with consideration of estimated graft patency rates), appropriateness of left internal mammary artery (LIMA) or bilateral internal mammary artery (BIMA) use [10, 11], appropriateness of radial artery use [12, 13], quantity and quality of vein available, and consideration for alternative sources should these be exhausted. Preoperative venous mapping may be obtained to locate and determine the presence and size of bilateral greater and lesser saphenous veins. Preoperative lower extremity arterial Doppler examination may indicate the most appropriate site for vein harvest, as the risk of wound infection and poor wound healing is likely to be increased in a lower extremity with peripheral vascular disease. Determination of the safety of utilizing the radial artery as conduit should be assessed with an Allen test.

Data review

A careful, *personal* review of available data cannot be stressed enough and is recommended prior to planning the operative procedure. This is particularly important as variations in study interpretation may exist. The anticipation of



(a) (b)

Figure 16.1 Posterior anterior (a) and lateral (b) chest x-rays depict significant calcification of the ascending aorta.

potential complications during this review may reduce their magnitude and severity.

A careful review of the *PA and lateral CXR* will alert the surgeon to aortic calcification, significant lung disease, significant cardiomyopathy, aortic dilatation, and mediastinal pathology. Significant aortic calcification (Figure 16.1) increases the risk of embolization and indicates a potential need for "aortic no touch" surgery with alternate cannulation sites and potentially circulatory arrest. Aortic calcification can be further evaluated utilizing CT scan (Figure 16.2) and by careful review of the left ventriculogram during left heart catheterization (Figure 16.3).

A wealth of information can and should be ascertained from the *cardiac catheterization* images. Prior to the injection of dye, calcified coronary arteries may be visualized. Significantly stenotic coronary arteries must be of sufficient size and have a patent, anatomically accessible location in order to accept a bypass graft. The size of the injection catheter utilized can often give an idea of the size of the vessel opacified. This is particularly helpful if magnification has been utilized to produce the images. Proposed target sites for bypass grafts must be free of significant calcium and stent material. Intramyocardial vessels may also be anticipated by viewing the injection through the cine cycle.

The left ventricular injection is particularly valuable because it provides an estimation of wall motion and ejection fraction. Prior to the injection of dye, a calcified aorta as well as calcified valve annuli and/or leaflets may be visualized. Injection of dye into the left ventricle also provides information regarding the size of the ascending aorta and an estimation of mitral valve competence. If a left ventriculogram is not performed, an echocardiogram should be done to assess left ventricular function and to evaluate for any suspected concomitant valvular pathology. In addition, injections of the descending aorta, renal arteries, or iliac vessels during left heart catheterization may provide additional information regarding significant peripheral vascular or renal artery occlusive disease. These data must be carefully considered when planning the operative approach in order to attempt to avoid potential complications.

Transthoracic or transesophageal echocardiogram will provide any information that may be lacking following cardiac catheterization in the assessment of

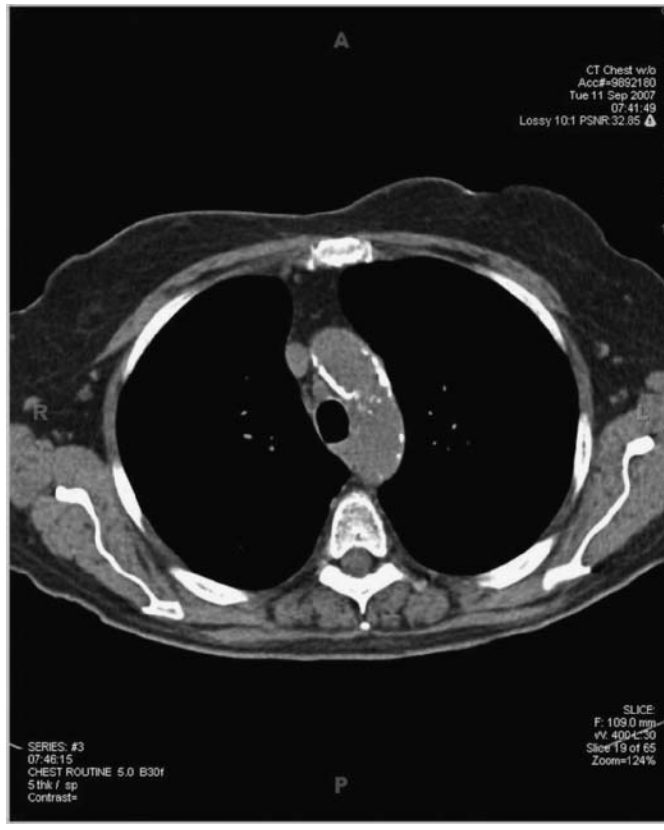


Figure 16.2 CAT scan of the chest without contrast depicts significant calcification of the aortic arch.

ejection fraction and valvular pathology. Should a significantly reduced ejection fraction be noted, an assessment of viability should be considered, as poor ejection fraction is a predictor for poor outcome following CABG. The descending aorta may also be imaged, and a significantly calcified descending aorta may denote a potential for embolization at the time of cardiopulmonary bypass.

Various pharmacologic as well as radiologic examinations may be obtained to determine *myocardial viability*. In order to provide benefit to the patient with significant graftable coronary artery disease and a significantly reduced ejection fraction undergoing CABG, the angiographically at-risk areas of myocardium must correspond to viable areas of myocardium. Large areas of nonviable or infarcted myocardium should alert the surgeon to heavily weigh the risk of surgical revascularization.

A *computerized tomography scan* of the chest or abdomen may provide valuable information regarding calcification of the aorta (Figure 16.2), the presence

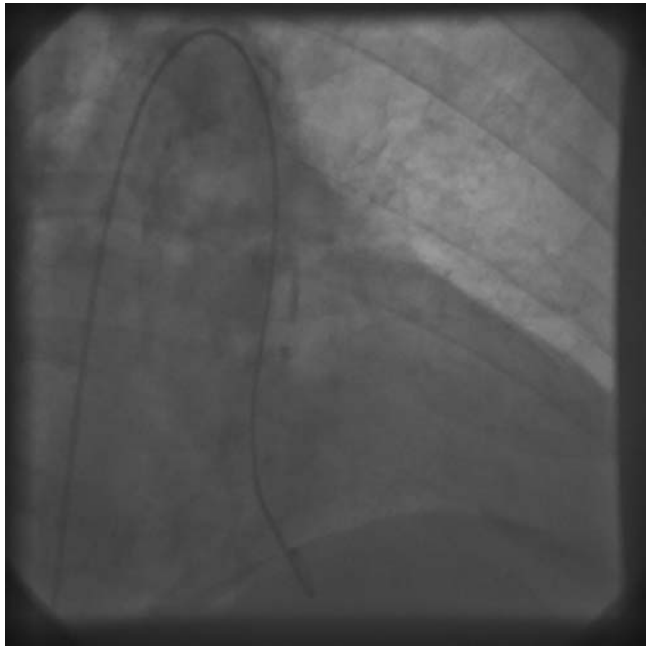


Figure 16.3 Left heart catheterization (left ventriculogram) prior to dye injection depicts a calcified aortic arch.

or lack of a tissue plane between the heart and the sternum in the case of redo surgery, significant lung pathology, and unexpected findings in other organs.

After a careful evaluation of the data available, a risk assessment may be derived and discussed with the patient. The timing of surgery and the operative plan may then be considered.

Timing of operation

Preoperative hemodynamic instability and/or unrelenting unstable angina often prompt urgent or emergent surgery. In stable patients, factors to consider when planning the timing of surgery include the time since cardiac catheterization, the administration of nephrotoxic medications or agents, and the baseline creatinine due to the risk of postoperative renal dysfunction [14]. Caution should be taken in the stable patient with an acute myocardial infarction in the setting of poor left ventricular function. Allowing recovery from the acute event prior to surgery may decrease morbidity and mortality [15].

Prohibitory systemic illnesses may also indicate a need for further workup or delay in elective surgery as well as additional consultations. Consideration should also be made for a delay in the stable patient when preoperative antithrombotic therapy has been administered due to the increased risk of perioperative bleeding. The Report from the STS Workforce on Evidence Based Surgery states that it is reasonable to discontinue clopidogrel for 5–7 days

Table 16.2 Important considerations for the operative plan.

Patient positioning/need for defibrillation pads
Use of agents to reduce bleeding
Need for special instruments or retractors
Cannulation sites
Type and frequency of cardioplegia delivery
Conduit
Need for cell saver
Cooling temperature on cardiopulmonary bypass
Backup plan (what if. . .?)

before CABG due to the increased risk of bleeding and that patients on glycoprotein IIb/IIIa inhibitors should be considered at high risk for bleeding depending on the half-life of the agent administered [16].

Operative plan

Careful planning of the procedure in advance will equip the surgeon with the ability to provide a calm and systematic resolution to unexpected operative findings. Prior to surgery, a "backup plan" should be considered in the event that the procedure does not proceed as planned. For example, the discovery of a porcelain aorta or a significantly dilated ascending aorta at the time of pericardiotomy would quickly warrant a change in the operative plan. Table 16.2 lists the operative plan details that may be considered prior to surgery.

Intraoperative management

Both the efficiency of the operative procedure and the achievement of its goal(s) will have a significant impact upon the postoperative course. In particular, a prolonged length of time on cardiopulmonary bypass significantly increases many postoperative complications. Therefore, an expeditious and technically successful operation will limit the risk of postoperative morbidity.

Sternotomy

Sternotomy that deviates from the midline may increase the risk of sternal fracture and will create difficulty during wound closure. Wires utilized for sternal closure may easily pull through the thinner side of bone increasing the risk of sternal dehiscence. Sternotomy that deviates from the sternum entirely necessitates fixation of each rib to the sternum and increases the risk of bony nonunion and sternal wound infection, particularly if bony segments remain mobile. Mobile chest wall segments also create difficulties with adequate broncho–pulmonary function postoperatively.

Redo sternotomy is particularly challenging. Appropriate steps should be taken to reduce complications including careful dissection superiorly and inferiorly beneath the sternum to develop a plane between the sternum and

mediastinal contents, consideration for a femoral arterial blood pressure monitoring line to guide rapid access to the femoral vessels for cannulation, confirmation that blood for transfusion is available in the room prior to incision, and preparation of the cardiopulmonary bypass machine with pump lines on the operative field prior to sternotomy. Even with the best preparation, injury of the mediastinal contents necessitating emergent femoral cannulation may occur during redo sternotomy.

Brachial plexus injury may occur during sternal retraction due to excessive stretch and fracture of the first rib or from excessive retraction of the internal mammary artery retractor [17]. Strategies to prevent this include a gradual opening of the sternal retractor to the least amount required for adequate visualization and the placement of the retractor low on the sternum [17].

Conduit harvest

Care should be taken during the internal mammary artery (IMA) harvest, as dissection and spasm of the conduit may occur from excessive traction or if small branches are avulsed. Due to its excellent patency, when utilized for the left anterior descending coronary artery graft and its benefit to survival, the IMA should be handled with great care. Visualization during its harvest may be aided by temporarily decreasing the tidal volume on the ventilator, placing a wet laparotomy sponge on the lung, or the temporary cessation of ventilation for particularly challenging areas. It should be remembered that a proximal injury may still permit its use as a free graft. Significant calcification is rare in the IMA; however, its presence warrants careful evaluation of the graft for acceptability as a conduit. The IMA bed also creates a potential site for occult bleeding that must be inspected prior to sternal closure.

Open, sequential incision (bridging), or endoscopic methods may be utilized to harvest saphenous vein for bypass conduit. Open or endoscopic methods may be utilized to harvest the radial artery. Endoscopic methods may reduce the risk of wound infection following conduit harvest (Figure 16.4) [18]. Calcification or spasm of the radial artery should warrant careful consideration for its use as a conduit. Careful visualization of the radial artery and ligation of branches is vital to prevent intraoperative or postoperative bleeding from the conduit bed. Significant postoperative bleeding resulting in a forearm hematoma or decreased distal motor or sensory function (particularly in the hand following radial artery harvest) warrants reexploration for bleeding and evacuation of hematoma. The meticulous handling of tissues and careful closure may reduce wound complications. In the interest of reducing cardiopulmonary bypass time, cardiopulmonary bypass should not be initiated until conduits are fully prepared and deemed acceptable.

Anticoagulation

Appropriate anticoagulation is required to prevent the devastating complication of clotting in the cardiopulmonary bypass tubing or oxygenator. Recognition and treatment of heparin resistance are important to provide

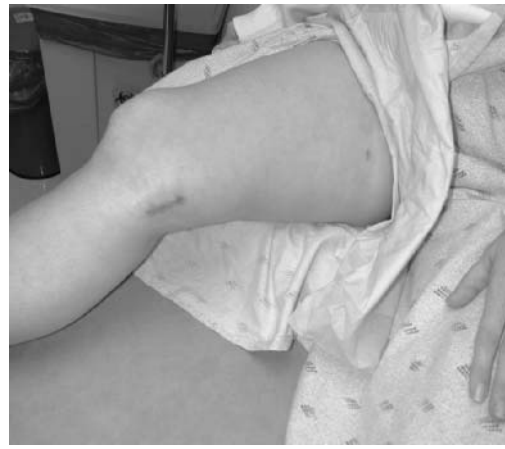


Figure 16.4 Postoperative photograph of saphenectomy wound following endoscopic harvest of vein for CABG at 4-week follow-up visit.

adequate anticoagulation when utilizing heparin. The risks and benefits of using antifibrinolytics should be considered on an individualized basis.

Cannulation

The use of epiaortic ultrasound will aid in locating the most suitable site for aortic cannulation in the patient with a heavily diseased aorta. Localization of a safe area in which to place the cannula will reduce the potential for embolization of material from the aortic wall. The discovery of a porcelain aorta should lead to the adoption of alternative operative strategies including alternative cannulation sites (femoral or axillary artery), consideration for replacement of the ascending aorta, consideration for circulatory arrest to perform proximal anastomoses, or conversion to off-pump CABG with an aortic "no touch" technique. The mean arterial pressure should be reduced during the time of cannulation of the aorta to reduce the risk of dissection and bleeding.

Careful attention to suture placement is required for cannulation of the right atrium or vena cava to prevent tearing of tissues and bleeding. Injury to the right coronary artery may occur with aggressive placement of a clamp near the right atrioventricular groove to facilitate cannulation of the right atrium.

The placement of an ascending aortic cannula for venting purposes or for the delivery of antegrade cardioplegia may be associated with a puncture of the back wall of the aorta or dissection of the ascending aorta. Familiarity and knowledge of the necessary force needed to place the ascending aortic catheter and awareness of this potential complication may aid in its prevention. Such injuries to the aorta require repair with cardiopulmonary bypass.

The blind placement of a catheter into the coronary sinus utilizing palpation alone or the delivery of retrograde cardioplegia at a high pressure via the coronary sinus catheter may be associated with rupture of the back wall

of the coronary sinus. This complication is best prevented by *gently* inserting the catheter and by the cessation of its advancement upon meeting resistance and by the careful monitoring of retrograde cardioplegia perfusion pressure during its delivery. Repair of this injury may be quite difficult due to the thin-walled nature of the coronary sinus and its proximity to the left circumflex coronary artery. Often direct suture repair of the coronary sinus is ineffective and a pericardial patch covering the entire area and coronary sinus ligation may be required.

Cross-clamp

Significant aortic disease as stated above may preclude placement of the aortic cross-clamp for CABG. Alternative cannulation sites for cardiopulmonary bypass would permit on-pump (to provide hemodynamic support) beating heart surgery utilizing off-pump positioning and stabilization techniques. Alternatively, conversion to off-pump CABG could be considered. Both alternative techniques may reduce embolization of particulate matter originating at the site of the diseased aorta.

The inadequate occlusion of the aorta by the cross-clamp during CABG will lead to increased myocardial temperature, poor myocardial protection, and distention of the heart. If necessary, the cross-clamp may be reapplied with the pump flow greatly reduced and the patient in Trendelenburg position. Multiple applications of the aortic cross-clamp should be avoided, if possible, due to the risk of embolization of particulate matter and the potential for resultant neurocognitive consequences [19, 20].

Strategies that will limit neurologic injury and the possibility of air embolism during and after cross-clamp removal include placement of an ascending aortic root vent, Valsalva maneuver or gentle massage of the left atrium with milking of the pulmonary veins to mobilize blood through the lungs and the left heart, de-airing proximal vein grafts, placement of the patient in Trendelenburg position, needle aspiration of the left ventricular apex, and observation of the left atrium and left ventricle for air by transesophageal echocardiography during ventricular filling.

Cardiopulmonary bypass

One of the most important strategies to avoid complications following on-pump CABG is to limit the time on the bypass machine. Prolonged cardiopulmonary bypass (CPB) time is a significant risk factor for postoperative morbidity and mortality. Strategies to avoid neurological injury during CPB include the following: minimize the use of cardiotomy suction, maintain an adequate mean arterial pressure, and maintain strict cooling and warming guidelines to reduce air precipitation [21]. Open and frequent communication with the perfusionist is vital to the early detection and avoidance of many complications during CABG.

Myocardial protection

There are multiple acceptable methods to deliver myocardial protection (antegrade, retrograde, warm, cold, tepid, crystalloid, blood, continuous, intermittent, etc.), and this will be addressed in a separate chapter focusing on this topic. Adequate myocardial protection must be provided in order to lessen the likelihood of inadequate myocardial function after CPB.

Coronary revascularization

An attempt should be made to provide complete revascularization to all angiographically at-risk myocardial territories, as incomplete revascularization is associated with decreased survival [22]. The target coronary artery is evaluated visually and by palpation to determine the most appropriate location for the distal anastomosis. This is done with the angiographic image in mind in order to appropriately revascularize the myocardium distal to significant stenoses. Sites with significant calcification in the vessel wall should be avoided. Suture needles often do not penetrate calcium and the vessel wall may tear, necessitating an endarterectomy in order to perform the anastomosis. Unplanned endarterectomy poses increased risk for embolization and dissection of the vessel as well as mortality [23]. If the target vessel is unsuitable due to size or calcification, or if a safe anastomosis may not be performed, then the option of concomitant or subsequent percutaneous intravascular intervention *may* still exist (hybrid revascularization procedure).

When performing an end-to-side distal anastomosis, it is important to appropriately fashion the size of the end of the conduit to the arteriotomy in the coronary artery to improve flow and patency of the graft. Additional technical pitfalls to avoid include placing stitches into the back wall of the coronary artery while constructing the anastomosis and taking inappropriately large bites (particularly at the toe of the anastomosis). A coronary artery probe may be utilized to confirm patency of a distal anastomosis prior to its completion.

If the left anterior descending (LAD) coronary artery has significant stenosis, every effort should be made to find a suitable site for placement of the LIMA, since this has been shown to prolong survival [10]. Visualization of the LAD can be made difficult by epicardial fat or by an intramyocardial course. Palpation of the LAD may be aided by the presence of a previously placed stent in the vessel. Additional maneuvers that may aid in its location include the following: tracing the vessel proximally if it is visible distally on the apex of the heart, visible diagonal vessels may be traced proximally, and retrograde cardioplegia may be administered to fill the vessel to aid in its palpation. It is important to remain humble and perhaps consider consultation with another surgeon intraoperatively for a fresh approach after a prolonged and unsuccessful search for the LAD. Consideration may also be given to grafting a suitably large diagonal vessel if no proximal stenosis exists.

Caution must be exercised in the construction of a redo LAD graft utilizing the IMA when a diseased but patent vein graft is already present. The initial flow of the IMA may be inadequate if the vein graft is ligated, and this

may be manifested by poor anterior wall motion upon attempts to wean from CPB. In such instances, a new vein graft, in addition to the LIMA, may be helpful.

When additional length is needed on an IMA graft to safely reach its target, careful fascial division in multiple different areas may often provide needed length. Too much tension on the anastomosis may decrease patency and increase the risk of avulsion of the pedicle from the coronary artery with heart manipulation and when left ventricular loading and ejection occur following cross-clamp removal. An additional lengthening strategy is to divide the pericardium at the location where the IMA enters the pericardium (with care not to injure the phrenic nerve).

If additional length is required on a vein or radial graft, a "T" anastomosis with a proximal end-to-side connection to the LIMA graft may be considered or the conduit may be placed on the aortic anastomotic hood of a previously completed graft. In this situation, however, inflow to both grafts will be dependent upon the inflow to the first graft (either at the proximal aortic anastomosis or the IMA). When conduit is limited, sequential distal anastomoses may also be performed in order to provide a complete revascularization. Again, flow into both coronary arteries may be jeopardized by a technical error in either anastomosis.

There are various acceptable sequences that may be utilized to perform coronary revascularization (distals followed by proximals, proximals prior to cross-clamp placement and then distals, construction and use of various "T" or "Y" grafts, etc.) as well as methods for sizing the length of bypass grafts originating on the aorta. It is advisable to have a system that is comfortable for the operator and can be repeated with each case ("do it the same way every time") in order to prevent an increased risk of complication.

Proximal anastomoses may be constructed with the heart arrested and cross-clamped or with the aid of a partial occlusion clamp when the heart is beating. Construction of the proximal anastomoses should occur in portions of normal aortic wall to prevent the risk of embolization of particulate matter and aortic dissection. This may be aided by palpation and epiaortic ultrasonic probe examination. An aortic punch or various anastomotic devices may be utilized. The size of the proximal end of the conduit should dictate the size of the aortic punch utilized. Increased frequency of aortic clamp placement has been associated with the risk of embolic events, as described above [19]. Care must be taken to ensure aortic bites that include the entire thickness of wall when performing the proximal anastomosis in order to avoid the risk of aortic dissection and bleeding.

Patency of bypass grafts may be assessed by the infusion of cardioplegia down the graft with a syringe prior to construction of the proximal anastomosis or by measuring flow using an ultrasonic flow probe placed on the completed graft (after weaning from CPB). This may alert the surgeon to potential problematic issues with the anastomoses such as graft kinking or graft spasm. The confirmation of adequate flow in grafts using a flow

probe is also particularly useful in the event of failure to wean from CPB following CABG.

Bleeding from anastomoses must be carefully addressed using adequate visualization techniques. Blind sutures in the toe of an anastomosis can compromise flow and result in graft occlusion. Visualization may be aided by replacing the cross-clamp and arresting the heart again or with the utilization of stabilizers that immobilize the heart for off-pump surgery that will allow immobilization while on bypass (beating heart). The incorporation of surrounding epicardial tissue in anastomotic repair sutures is often helpful in obtaining hemostasis.

Weaning from cardiopulmonary bypass

During the weaning process from CPB, the surgeon should maintain open communication with both the perfusionist and the anesthesiologist. Failure to wean from CPB may have multiple etiologies: a technical problem with bypass graft(s), incomplete and inadequate myocardial protection, myocardial stunning, air embolus to a coronary artery, drug reaction, excessive bleeding, or other factors. A systematic review of possible etiologies should be undertaken. Flow may be checked in the grafts and transesophageal echocardiogram may alert the surgeon to specific wall motion abnormalities. The passage of time and elevation of the mean arterial pressure following resumption of CPB will often lead to improvement in myocardial function following coronary arterial air embolus. Inotropic and mechanical (intra-aortic balloon pump placement or left and/or right ventricular assist device placement) support may be necessary to separate from CPB.

Following the successful wean from CPB, the cardiotomy suckers should be turned off prior to the completion of protamine administration to avoid the formation of clot in the CPB machine. This ensures the option of subsequently returning to CPB should other complications occur. The reversal of heparin with protamine may potentially result in a range of allergic reactions with which both the surgeon and the anesthesiologist should be familiar [24].

Postoperative care

The overall rate of major morbidity or operative mortality in the 2008 STS Report (including all of year 2008) for patients undergoing isolated on-pump CABG was 16.9% (risk adjusted rate 13.6%) [1]. *Providing* the patient with a technically successful and complete myocardial revascularization is the first step in reducing postoperative morbidity. Postoperatively, an adequate cardiac index (> 2.0 L/min/m^2) should be maintained with the use of inotropic or mechanical support as needed, as a reduced cardiac index is associated with poor survival [25].

Graft failure or coronary spasm

Graft patency may be enhanced by the administration of antiplatelet agents including aspirin and/or Plavix that are reinstituted when safe, the use of inotropes or mechanical support to maintain an adequate cardiac output, and the use of calcium channel blockers or nitrates for the prevention of arterial graft spasm [13].

Continuous electrocardiogram monitoring is utilized in the early postoperative period to immediately detect ischemic changes that may be indicative of graft closure or graft or native vessel coronary spasm. The awake and alert patient may complain of chest pain in this situation. Unexplained hypotension, cardiogenic shock, and unexplained arrhythmias may also indicate myocardial ischemia. An urgent transthoracic echocardiogram may reveal wall motion abnormalities. A high index of suspicion for myocardial ischemia or graft compromise must be maintained, and early coronary angiography with possible angioplasty or stent placement may be indicated to diagnose and/or treat such conditions. In addition, a prompt return to the operating room may also be indicated.

Infection

The STS 2008 Report observed rate of deep sternal wound infection was 0.4% (risk adjusted 0.3%) in patients undergoing isolated CABG [1]. Perioperative intravenous antibiotics are administered prior to incision and continued for 48 hours or less postoperatively. Additional antibiotic use should be guided by specific culture and sensitivity studies. In addition, aggressive blood sugar management (often with insulin infusion) is utilized to limit the occurrence of sternal wound infection [2, 3, 26]. Central lines and chest tubes are promptly discontinued when no longer necessary or useful. In addition, other sites (conduit harvest sites, urinary tract, and lungs) are closely monitored and promptly treated should an infection occur.

Postoperative bleeding/early tamponade

Most importantly, appropriate surgical hemostasis should be obtained prior to chest closure to avoid postoperative bleeding. In the postoperative period, coagulopathy is corrected with appropriate blood products, patients are adequately warmed if hypothermia exists, and chest tubes are frequently monitored for patency to prevent tamponade. Tamponade requires immediate operative drainage. Heparin rebound should be considered as a possible cause for continued bleeding. The postoperative CXR may indicate an undrained hemothorax that may require surgical reexploration in the case of excessive bleeding.

Renal failure

The STS 2008 Report observed rate of renal failure (postoperative creatinine > 2 mg/dL or doubling of the preoperative creatinine) following isolated CABG in patients not previously on dialysis was 3.7% (risk adjusted 3.2%)

[1]. To limit renal injury in the postoperative period, an acceptable cardiac index and mean arterial pressure must be maintained. Nephrotoxic agents should be avoided or limited, and any renally excreted medication should have dose adjustment [4]. Renal injury postoperatively may be multifactorial, unpredictable, or related to the intraoperative course.

Cerebrovascular accident

The STS 2008 Report observed rate of permanent stroke in patients undergoing isolated CABG was 1.3% (risk adjusted 0.9%) [1]. Neurologic complications may be manifested by a wide range of signs and symptoms from delirium and confusion to permanent stroke. These complications may also be directly related to intraoperative or perioperative events. Similar to the strategy to prevent renal injury, an acceptable cardiac index and mean arterial pressure must be maintained. Patients with postoperative atrial fibrillation or documented poor ejection fraction with intracardiac clot should be anticoagulated to prevent cerebral embolization.

Respiratory failure

The STS 2008 Report observed rate of prolonged ventilation in patients undergoing isolated CABG was 11.6% (risk adjusted 8.8%) [1]. Prolonged ventilation is defined by the STS as greater than 24 hours on the ventilator. Many preoperative risk factors may indicate a higher risk for the development of respiratory failure in the postoperative period. A prompt postoperative trial of extubation when appropriate, the limitation of sedation, tracheostomy, and early nutritional support may be appropriate in the individualized care of these patients. Appropriate antibiotics are administered when ventilator-associated pneumonia occurs as a result of prolonged intubation.

Urinary tract infection

In an attempt to combat urinary tract infections postoperatively, indwelling urinary catheters are removed promptly, urinary retention is treated aggressively, and antibiotics are administered when appropriate.

Gastrointestinal complications

As with many postoperative complications, the risk of gastrointestinal complications increases as CPB time increases. The prompt diagnosis and treatment of gastrointestinal complications following CABG requires a high index of suspicion. Gastrointestinal ischemia may occur following periods of hypoperfusion due to low cardiac output, hypotension from blood loss, and as a result of intravascular emboli [27]. Gastrointestinal bleeding may be exacerbated by the use of antiplatelet agents and anticoagulation. Adequate gastric mucosal protection should be provided with proton pump inhibitors to prevent stress ulceration. In addition, early enteral feeding should be initiated in the case of prolonged ventilation. Antibiotics should be discontinued

promptly when they are no longer clinically indicated to prevent the complication of *Clostridium difficile* diarrhea and colitis.

Atrial fibrillation

Postoperative atrial fibrillation is the most common cause of morbidity following isolated CABG as it occurs in up to 40% of patients [28, 29]. The onset of postoperative atrial fibrillation prolongs the length of hospitalization and increases hospitalization costs. Medical therapy to limit heart rate (β blockers and calcium channel blockers) and to attempt medical cardioversion (amiodarone), electrical cardioversion, and anticoagulation are utilized in the postoperative treatment of this arrhythmia.

Delayed tamponade

Tamponade occurring after the acute postoperative period may be extremely difficult to diagnose, and a high index of suspicion for this diagnosis must be maintained. A decline in renal or liver function, poor urine output, or an elevated coagulation profile may be the initial clue. An echocardiogram may be helpful in making the diagnosis. This complication must be rapidly treated with reexploration of the chest and evacuation of the mediastinal fluid.

Summary

On-pump CABG is a commonly performed procedure with acceptably low mortality and morbidity rates. Careful preoperative planning and a technically complete and expeditious revascularization will limit many potential complications.

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CHAPTER 17

Off-Pump Coronary Artery Surgery: A Safe Approach

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Introduction

Off-pump coronary artery bypass surgery (OPCAB) seeks to avoid the documented physiologic insults of extracorporeal cardiopulmonary bypass (CPB) to various organ systems. Data from the SMART trial from our institution have shown excellent results for OPCAB [1, 2]. The 2004 ISMICS Consensus statement has pooled data showing that OPCAB can be done with equal or better results in the low to medium risk patient and especially favors patients with a high-risk profile [3]. Recent reviews from the Society of Thoracic Surgeons' National Cardiac Database showed that risk-adjusted morbidity and mortality were reduced after OPCAB compared to conventional on-pump coronary artery bypass surgery. This was especially true for female patients as well as for patients requiring many ($\geq$4) or few ($\leq$3) grafts [4, 5].

The OPCAB surgeon is uniquely able to adopt techniques minimizing manipulation of the aorta and should also expand the utilization of arterial grafts. These paradigm shifts promise to significantly reduce the risk of stroke and increase the quality and longevity of surgical coronary revascularization. The combination of these strategies may well provide superior and more durable results with surgical coronary revascularization than those that have been previously achieved and may represent the most compelling surgical alternative to percutaneous coronary intervention.

OPCAB has a definite learning curve and is technically demanding. OPCAB requires a dynamic team approach to ensure success. The heart should not be the only thing that is moving; both the surgeon and the anesthetist must be on the move as well. In this chapter, we will discuss the fundamentals of time-tested, safe, reliable and reproducible OPCAB at our institution.

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Preoperative planning

Every patient has a complete history and physical examination. All patients have serum blood glucose and glycosylated hemoglobin (HbAIc) levels drawn. Bilateral IMAs are used in patients younger than 75 with HbAIc levels less than 7.0. Well-controlled diabetes is not considered a contraindication for bilateral IMA grafting at our institution. Uncontrolled blood sugar on admission is aggressively controlled preoperatively before OPCAB.

Carotid artery duplex is obtained on all patients aged greater than 65 years, and/or those with left main coronary artery disease, peripheral vascular disease, diabetes, smokers, and those with history of stroke and/or transient ischemic attack. At our institution, staged carotid endarterectomy (CEA) is aggressively undertaken in patients with symptomatic stenosis or stenosis greater than 75% with peak flow velocities greater than 350 m/s systolic and 140 m/s diastolic, even if asymptomatic. If there is any discrepancy between the clinical impression and vascular Doppler measurements, an MRI/MRA of the neck vessels is done to further assess the severity of lesions. When indicated, CEA is preformed under local anesthesia, 24–48 hours before the planned OPCAB, with a stroke risk of about 1% in our institution. If the coronary lesions are very critical and coronary revascularization is urgent or emergent, CEA is performed under anesthesia with vascular shunting immediately prior to the OPCAB procedure. The Asymptomatic Carotid Atherosclerosis Study had an inclusion criteria of 60% stenosis, and clearly favored CEA over medical management (5.1% vs. 11% 5-year aggregate risk of neurologic event, respectively) [6].

Patients with significant chronic obstructive pulmonary disease have pulmonary function tests performed. Profoundly impaired pulmonary function is a relative contraindication to harvest of bilateral IMAs.

Ventricular function is documented either with echocardiogram or left ventriculography at the time of the coronary angiography. Cardiac murmurs on physical examination are further investigated with echocardiography. Significant aortic or mitral disease may preclude safe OPCAB. Moderate mitral regurgitation should alert the OPCAB surgeon to possible hemodynamic difficulties intraoperatively. Profoundly depressed left ventricular ejection fraction may necessitate the planned use of IABP intraoperatively.

All patients have clinical Allen's test for suitability of radial artery harvest. Saphenous vein mapping using Duplex scan is obtained when clinical doubts of usability exist.

The coronary angiogram is carefully reviewed to plan the number of grafts, the choice of conduits, and the operative strategy for OPCAB grafting.

Radial artery. We use the radial artery when the degree of coronary stenosis is greater than 90%. With a single IMA, we prefer to use the radial to the second most important left-sided coronary artery. When utilizing bilateral IMA grafts, if the right IMA goes to the left system, the radial may be used to graft the distal right coronary artery (RCA) system.

Right IMA. This conduit is almost always taken as a skeletonized conduit beyond its lower end bifurcation. On the right side, the in situ right IMA will usually reach the mid RCA, less frequently the distal RCA and least frequently the posterior descending artery (PDA). On the left, when taken through the transverse sinus posterior to the ascending aorta and main pulmonary artery, the in situ right IMA usually will reach the proximal circumflex, the proximal anterolateral obtuse marginal (OM1) and less frequently the middle OM and infrequently the posterolateral OM.

Alternative strategies may include the following. If the in situ right IMA is too short to reach the left circumflex target, the right IMA may be directed to the LAD and the left IMA to the left circumflex. Otherwise the right IMA can be divided proximally and a T-graft composite constructed off the left IMA; the right IMA may then be anastomosed to any branch(es) of the left circumflex coronary artery.

Left IMA. A skeletonized left IMA can frequently be used to sequentially graft the diagonal branch and then the LAD. When used to graft the left circumflex system, the left IMA may be used to sequentially graft two or more OM branches.

Saphenous veins. In coronary arteries with 60–80% stenosis the radial artery is usually not chosen, due to concern about competitive flow in the native coronary artery and subsequent development of a "string sign" in the reactive radial artery. In such target, coronary arteries, IMA grafts, or saphenous vein are used. The saphenous vein conduit is preferred for grafting the moderately stenosed RCA system than to the left coronary system.

Operative steps

Preinduction preparation

Maintenance of core-body normothermia is critical in OPCAB. Postoperative hypothermia after OPCAB may lead to coagulation abnormalities, as well as delay the progress and extubation of the patient [7]. The patient is placed on a thermal pad composed of an adhesive hydrogel warming system (Kimberly-Clark Health Care, Georgia, USA) that continuously circulates warm water to the patient's back and flank. This appears superior to convective forced air systems [8]. The operating room is kept warm—at least 75 degrees Fahrenheit. Unlike on-pump CABG, there is no means to rapidly warm the patient at the end of the operation with OPCAB.

The patient is attached to ECG leads, IABP leads if severe left ventricular (LV) dysfunction is an issue, an arterial line avoiding the left radial conduit, central venous line, Swan Ganz catheter, and Foley catheter with temperature probe. The opening pulmonary artery and right atrial pressures are noted. The heart rate is noted, especially if it is slow. Cardiac index is obtained. A femoral arterial line is placed if IABP use is remotely anticipated, so that expeditious placement can be instituted in the event of hemodynamic compromise. Transesophageal echocardiogram probe is carefully placed and is generally useful

during OPCAB and especially in those with mitral valve regurgitation and impaired left ventricular function.

The radial artery is again and finally tested using the oximetric probe. The isolated ulnar artery circulation should produce a good independent pulse waveform and digital oxygen saturations recorded by the probe placed on the index finger, while the radial artery is occluded. The radial artery should also show good independent waveform and saturations.

Intravascular volume is repleted with crystalloid at a rate of 500 mL/h. Patients with very low filling pressures may occasionally require optimization of volume status by bolus(es) of crystalloid prior to cardiac displacement. Administration of excessive intravenous fluid should be scrupulously avoided. Inotropes and pressors are kept handy and are preferred over excessive intravenous fluids. Short acting and intermediate anesthetic agents are used.

The CPB machine is kept ready in the OR. It is "primed" prophylactically for patients with severely diminished LV function and at the first sign of hemodynamic deterioration for all other patients. A skilled, certified perfusionist is present in the OR throughout the entire OPCAB procedure. The red blood cell salvage machine is run by the perfusionist and is used in every case.

The surgeon's sketch of the patient's coronary arteriogram, with specific notes regarding conduit choice and any anticipated operative challenges should be displayed within sight of the surgeon throughout the case, so that he may refer to it at any time conveniently during the course of the operation.

Postinduction preparation

All patients are given Aspirin 600 mg inserted per rectum prior to skin preparation and surgical draping. Antibiotic is given before the start (Cefuroxime 1.5 gm or Vancomycin 1 g i/v if penicillin allergic) of the operation.

Cell saver suckers are connected on the operative field. Atrial and ventricular "alligator" pacing clips are passed off to the anesthesiologist. A working pacemaker box must be present and tested in the anesthesiologist's workspace. The internal defibrillator paddles are passed off and tested prior to the skin incision.

Surgery

Sternotomy. For a bilateral IMA harvest, it is paramount that the sternotomy is in the midline. An asymmetric sternotomy increases the risk of mechanical insecurity with increased risk of dehiscence and infection. In addition, on the side of the thicker plate of sternum, the IMA is more distant from the surgeon, increasing the difficulty of harvest.

An absorbable type of bone "wax" Ostene^{R} (Ceremed Inc, Los Angeles, California, USA) may be applied immediately after sternotomy to minimize bleeding from the sternal marrow. Ostene is a water-soluble mixture of alkylene oxide copolymers and remains at site only for 24–48 hours. We kneed

lyophilized vancomycin powder into this material prior to use [9]. We avoid bone wax that impairs bone healing.

While IMAs may be harvested without violating the pleural cavity, we routinely choose to completely open the left pleural space. This facilitates a more complete harvest and a longer IMA conduit which may be positioned posterior to the apex of the left lung at the end of the case, thus reducing the risk of tension on the in situ IMA caused by the motion of the left lung during ventilator weaning or coughing. Bilateral IMAs may be harvested either with the use of diathermy and titanium hemostatic clips or with the use of the ultrasonic scalpel. We prefer to use the ultrasonic HARMONIC^{TM} scalpel (Ethicon Endo Surgery, Cincinnati, Ohio, USA). With the ultrasonic technology, there is minimal lateral thermal tissue damage with minimal charring and desiccation. When the diathermy (ValleyLab, Colorado, USA) is used, the coagulation power is set at 15–20 watts. The use of clips can lead to trauma and small subadventitial hematomas and intimal "denting." The HARMONIC scalpel seems less prone to cause this. Moreover, if hemostasis of IMA branches depends upon clips, problematic bleeding may occur if a clip is dislodged during passage of the right IMA through the transverse sinus to graft the left circumflex system. Such a bleeding branch may be inaccessible after construction of the distal anastomosis. This is another advantage of the harmonic scalpel.

We use special, modified IMA forceps (Scanlon, Minneapolis, MN, USA) with a bend to allow better visualization of the IMA during harvesting. One should be gentle when grasping the adventitia of the IMA to avoid hematomas. Scrupulous technique during harvest will avoid injury to the collateral veins on the chest wall and maximize the benefits of a skeletonized harvest.

We prefer papaverine as our IMA vasodilator agent [10]. We do not inject papaverine into the lumen of skeletonized IMAs after the harvest and before clipping the cut end, as the lack of collateral circulation tends to create intimal precipitation and deposits and possible chemical injury to the intima. Topical papaverine is applied directly to the outside of the harvested IMAs and a gauze sponge soaked in papavarine solution is wrapped around the skeletonized IMA. However, for the pedicled (nonskeletonized) IMA, we inject intraarterial papaverine using an atraumatic silastic olive-tipped needle and clip the end of the artery.

Hemostasis. It is very important in OPCAB to prevent any avoidable blood loss. Excessive blood loss wastes clotting factors and platelets, which are not returned to the patient by the cell salvage machine. The use of more than three cell saver retransfusions may lead to an obvious on-table coagulopathic state, with a dose-response such that increasing numbers of cell saver units produce a worsening coagulopathy. Meticulous technique is thus very important to achieve a bloodless operative field. During IMA harvest one should intermittently suction the pleural space dry. One should address the IMA side branch or bed bleeders if there is intermittent excessive pleural blood return and not wait until the end of the case.

Pericardial preparation

Open book stitch/left pericardial stitch

The pericardium is an ally of the OPCAB surgeon and it should be used to the maximum advantage to allow complete cardiac visualization. After opening the pericardium in the midline, the incision is "T" 'd along the diaphragmatic edge beyond the apex of the heart. The apex of the heart must be cupped and displaced to the right to facilitate completing the pericardial incision. The fat pad overlying the pleural surface of the pericardium is also divided and detached from the diaphragm. The surgeon must visualize and avoid injury to the left phrenic nerve at the deeper end of this T. The heart is lifted gently out of the pericardial well and a pericardial stitch is placed on this mobilized left pericardial flap just above the phrenic nerve. Upward traction on this stitch should now displace the heart rightward and easily bring the LAD into view. This creates the equivalent of an open book left pleuro-pericardial well, detached from its diaphragmatic attachment and raises the bed of the pericardium and heart with traction.

Pericardial stitches are placed on the right edge but not placed on traction, except when grafting the RCA or performing aortic proximal anastomoses. The other end of the T-incision is extended along the right diaphragmatic edge. In the case of severe cardiomegaly, difficult OM targets or bilateral IMA harvest, the right pleural space can be formally opened longitudinally, avoiding injury to the right phrenic nerve. The diaphragmatic muscle slips which insert to the right side of the xiphoid are divided and this allows elevation of the right sternal border. This will accommodate the rightward dislocation of the heart without compromising caval inflow.

Deep pericardial stitch (DPS)

The apex of the heart is cupped and gently lifted out of the pericardial well, the base of the well is suctioned out and a heavy silk stitch is placed very close to the base of the heart and at a point 2/3 to the left between the IVC and left inferior pulmonary vein. This needle should pass through the posterior pericardium without injuring the left lower lobe of the lung, the esophagus or descending aorta. A rubber Rummel tourniquet is placed on the stitch to prevent the silk from chafing the epicardium (Figure 17.1).

The combination of the left pericardial stitch and the deep posterior pericardial traction stitch will expose the LAD and the lateral wall of the heart most adequately in most patients. Caudal traction of the DPS along the diaphragmatic edge will expose the PDA and the inferior surface.

Placing a warm wet pad behind the lateral aspect of the heart will also help displace the heart to the right and expose the LAD and diagonal.

Two other pericardial maneuvers are needed. The left phrenic nerve is clearly visualized on the mediastinal pleural surface. A vertically oriented U-incision is made lateral to the main pulmonary artery to just above the phrenic to allow the left IMA to hang downward as it enters the pericardial

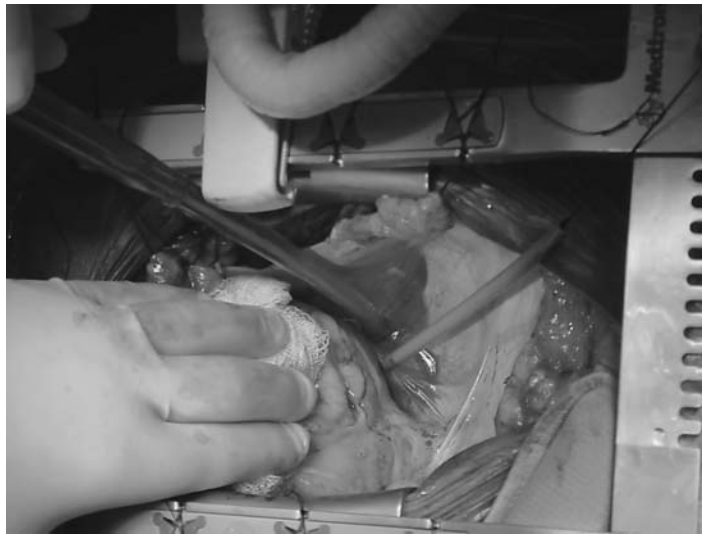

Figure 17.1 Deep pericardial stitch placed at a point 2/3 to the left between the IVC and left inferior pulmonary vein.

space, avoiding both kinking/compression on the pericardial edge and possible traction by the apex of the left lung. If the right IMA is used as an in situ graft to the left circumflex territory, a generous longitudinal incision is made in the right pericardium anterior to the right phrenic nerve. The right IMA is then passed through this pericardial incision and through the transverse sinus to approach the left circumflex territory. If the edge of the pericardial incision threatens to kink or compress the right IMA as it enters the pericardial space, the pericardium may be carefully "T" 'd into the transverse sinus with scissors, taking care to avoid injury to the right phrenic nerve, which may be gently mobilized out of harm's way.

Epiaortic ultrasound

Next, we perform an epiaortic ultrasound and assess the aortic atheroma burden. Our grading system based on the worst region of the ascending aorta is shown in Table 17.1. Transesophageal echocardiogram is less accurate for this purpose [11]. A strategy is then made for the proximal anastomosis approach.

If the aorta is grade I or II, we separate it from the pulmonary artery in anticipation of using a side-biting clamp. Such a separation in the loose areolar plane between the two vessels is helpful to prevent the side-biting clamp from slipping during completion of the anastomosis. It is also important not to denude the aorta as this may make the aorta more vulnerable to injury from the partial clamp, especially in the elderly, frail patient.

Table 17.1 Intraoperative epiaortic ultrasound.

Grading of ascending aorta	*Aortic side clamp*	*HEARTSTRING*
I (wall $<$ 2 mm)	Yes	Yes
II (2 $\leq$ wall $<$ 3 mm)	Yes	Yes
III (3 $\leq$ wall $<$ 4 mm)	No	Yes
IV (wall $\geq$ 4 mm)	No	Yes[a]
V (mobile atheroma with free floating tip)	No	Yes[a]

[a]The HEARTSTRING device (described later) may be used in the ascending aorta with focal Grade III, IV or V disease if a less diseased (Grade I or II) area of the anterior wall can be located by epiaortic ultrasound [12].

Guidelines for planning the sequence of distal anastomoses

1 Graft completely occluded and collateralized vessel(s) first.
2 Graft collateralizing vessel(s) after reperfusing collateralized vessels.
3 Perform proximal anastomosis first or immediately after distal anastomosis if coronary target is a critical collateralized vessel. This minimizes ischemia when occluding the collateralizing ("feeding") vessel next.
4 Beware of occluding a large dominant RCA proximal to the origin of the atrioventricular (AV) nodal artery. This can lead to bradycardia and severe hemodynamic compromise. The use of temporary pacing and/or coronary shunts should be readily available.

Usually the left IMA to the LAD anastomosis should be constructed first, particularly when the LAD stenosis is very severe and very proximal or in the case of left main stenosis. This assures immediately available new blood flow to the anterior wall and septum and allows the heart to better tolerate further manipulation. However, if the LAD is a collateralizing vessel for a tight right and circumflex lesions, it may be ill-advised to start with the LAD, especially without the use of an intracoronary shunt.

Using suction-based cardiac positioners and coronary-stabilizing devices

Although there are several satisfactory alternative devices available, we prefer the Medtronic Octopus^{R} Evolution Stabilizer and the Medtronic Starfish^{TM} 2 Apical Suction positioning device (Medtronic, Minneapolis, Minnesota, USA) [13]. Apical suction devices permit effective displacement of the heart without compression. This minimizes hemodynamic compromise.

Our preferred configurations for traction sutures, positioner (Starfish), and stabilizer (Octopus) for each coronary territory are described below. The sternal retractor is placed with the transverse bar at the caudal end of the sternotomy.
1 *LAD/diagonal*. (See Figure 17.2.) The deep pericardial traction suture is pulled upward to the left and a gauze pad sometimes placed under the apex

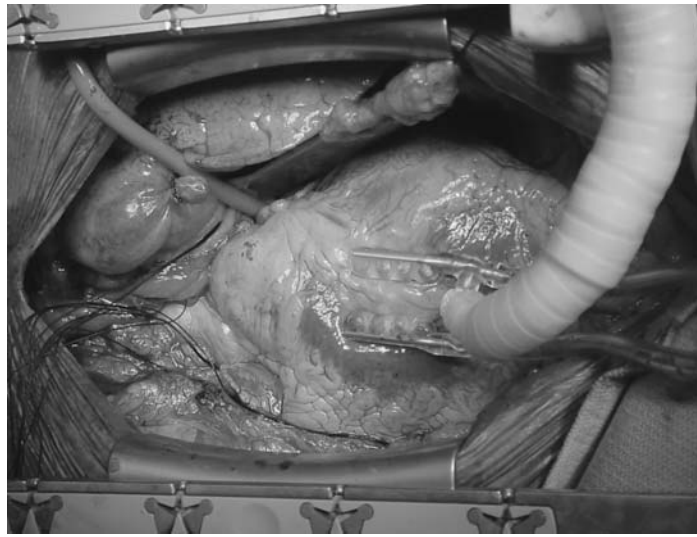

Figure 17.2 The left pericardial stitch is pulled tight. The DPS is pulled upward and to left shoulder. The right-sided pericardial silk stays have all been relaxed. The Octopus Stabilizer is placed over the clearly accessible LAD. The diagonal vessel is also clearly seen.

of the heart. The stabilizer (Octopus) is placed on the transverse bar of the sternal retractor to the left edge. The positioner (Starfish) is usually not needed but can be placed on the right side of the sternal retractor with the axis of traction caudally and obliquely to the right to align the LAD a little to left of midline.

2 *Circumflex and OM*. (See Figure 17.3.) The deep pericardial traction suture is pulled upward to the left and slightly cephalad. The positioner is generally used and is placed on the cranial end of the right side of the sternal retractor, and the suction cup is positioned on the obtuse margin of the heart (not on the apex). The pull is exerted upward, caudally and to the right. The stabilizer is placed on the caudal end of the right side of the retractor or alternatively on the transverse bar of the sternal retractor toward the right. Make sure all right-sided pericardial stay sutures are relaxed. The operating table is steeply rotated to the right. The right pleural cavity is widely opened if hemodynamic instability results from compression of the right atrium or ventricle against the right pericardium or sternal retractor or if additional cardiac displacement is needed to provide coronary visualization.

3 *PDA*. (See Figures 17.4 and 17.5.) The inferior right pericardial stay suture may be taut, while the left-sided pericardial suture is partially or fully relaxed; the deep pericardial traction suture is pulled caudally in the midline. The positioner is placed on the cranial end of the right side of the sternal retractor, with apical cup on the apex lifting it straight up. Try not to buckle the axis of the heart by excessive cranial traction. A steep Trendelenburg positioning of the operating table further aids in visualization of the base of heart and

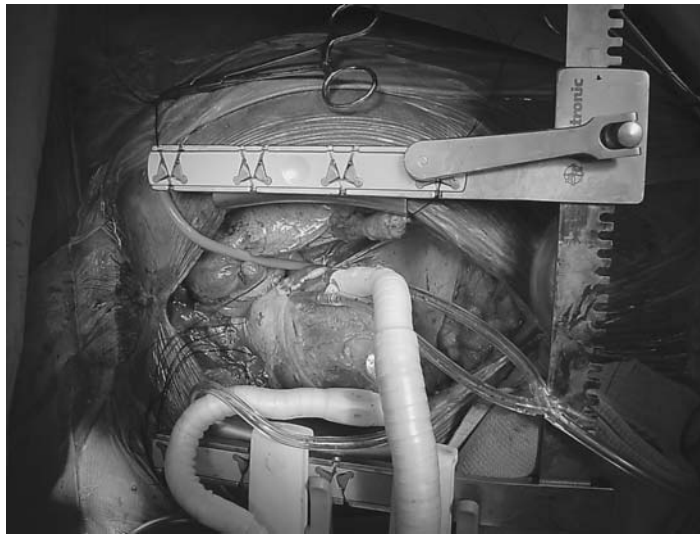

Figure 17.3 The Starfish lifts the heart upward, table is rotated downward and to the right. The DPS is pulled upward and to the left shoulder. The right-sided pericardial sutures are relaxed. A folded towel under the right inferior end of the sternal retractor serves to lift the right hemisternum. The Octopus is applied over the OM vessel.

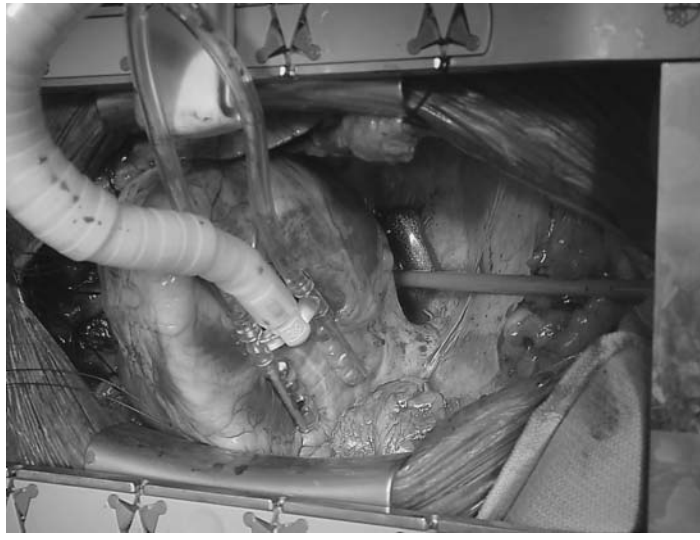

Figure 17.4 DPS is pulled upward and toward the feet. Steep table downward position exposes the inferior surface of the heart. The Octopus is placed over the PDA. The Starfish was not necessary in this case.

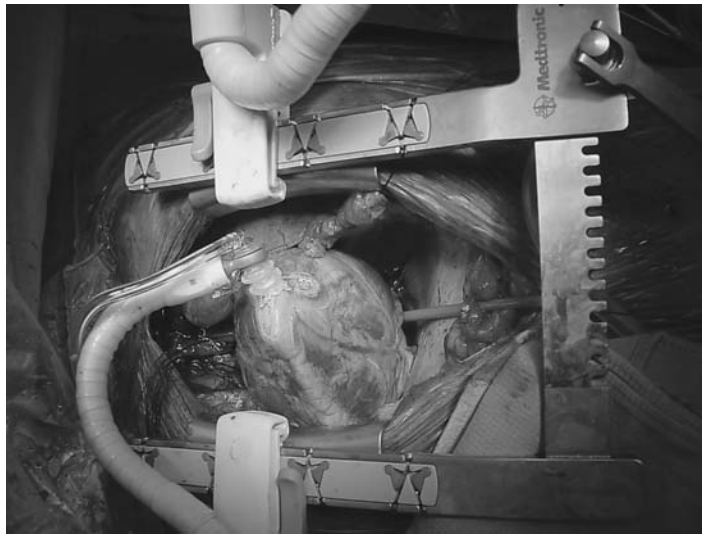

Figure 17.5 In other cases of PDA exposure, the Starfish and steep table downward position bring the inferior surface of heart into view. The Octopus seen on the left sternal blade is about to be applied on the PDA.

importantly helps in preventing buckling of the AV axis. The stabilizer is placed on the cephalad half of either the right or the left bar of the sternal retractor.

4 *Distal right coronary*. The deep pericardial traction suture is gently pulled caudally. The positioner is placed on the cranial end of the right or left side of the sternal retractor, and the suction cup is applied to the acute margin of the right ventricle, lifting it anteriorly and cephalad. The stabilizer is placed on the lower half of either the right or the left bar of the sternal retractor; its articulating arm curves around the heart, following the AV groove, to approach the distal RCA.

It is critically important to release all the right-sided pericardial sutures when dislocating the heart for left-sided exposure. Elevation of the right sternal edge of retractor with a folded towel(s) also creates more space to accommodate the heart, avoiding compression of the right heart against the sternal edge.

These particular apical suction configurations described lift the heart out by pulling it and not pushing it. This minimizes compression of the atrial and ventricular cavities, optimizing hemodynamic stability. With suction stabilizers, it is also important to avoid compressing the heart in an effort to achieve immobility. Excessive compression for the diagonal can compress the LAD or left ventricular outflow tract. It is important not to pull the heart cephalad in an extreme fashion that "buckles" the longitudinal AV contracting axis of the heart and the mitral valve, creating ineffective ventricular contraction and/or mitral incompetence.

Technique for placement of suction devices on the epicardium

The improved malleability of the Medtronic Octopus^{R} Evolution stabilization pods is very useful on curved surfaces of the heart or on irregular epicardial fat. It is important to mold the malleable pods in such a way that all the suction cups make uniform contact with the epicardium. An audible sucking sound is a clear indication that there is loss of contact between a cup(s) and the epicardium. Visually identify which cup has lost contact and mold the pods accordingly. The suction on the stabilizers should be set around negative 150 mm Hg initially and can be increased if needed. Before making contact with epicardium, the two Octopus^{R} Evolution pods should be squeezed together at the ends, so that when positioned on the epicardium and released, the tension in the improved construction of the wire-loop headlink will exert lateral traction to open up the coronary for optimum stabilization and exposure. Otherwise the epicardial fat tends to bunch up, "guttering" the coronary and will make the coronary visualization less ideal.

After the suction pods are applied on the heart, the mechanical arm of the stabilizer is tightened. The motion of the pods attached to the epicardium should be mentally studied carefully in systole and diastole. The mechanical arm should be tightened with the pods in the median position of the oscillation between systole and diastole (mechanical median of the cardiac cycle). This concept of a "mechanical median" is crucial for optimal immobilization without compression of the heart. Furthermore, it is important to understand that more compression can paradoxically result in more and not less movement of the stabilized anastomotic site and deterioration of hemodynamic stability.

"Apical" suction devices may be used on any surface of the heart and can be used in multiple configurations. It is important to place them on relatively smoother regions of the epicardium, without epicardial fat crevices that can disrupt the vacuum created by the positioner. The average suction required ranges from negative 100 to 250 mm Hg. Suction in excess of negative 350–400 mm Hg can create subepicardial hematomas in patients with frail tissues. Small subepicardial hematomas can be ignored. Large or freely bleeding subepicardial hematomas should be repaired with local manual pressure and fibrin sealants injected beneath the epicardial peel after heparin reversal. It is best to avoid pledgeted sutures. It should not be assumed that a bleeding epicardial hematoma will stop bleeding after chest closure. Importantly, in over 4000 OPCAB cases, we have not seen any coronary artery vascular injury from the use of suction-based cardiac positioning and stabilization devices.

Mechanisms underlying hemodynamic compromise and corrective actions

It is critical for the anesthesia and surgical teams to monitor constantly the heart rate, systemic and pulmonary blood pressures, and the ST segments

on the continuous ECG tracing. Abnormalities in any of these values require prompt attention; accepting delays in correction can lead to emergency conversion to CPB with increased mortality and morbidity.

A good understanding of the mechanisms of hemodynamic instability during OPCAB maneuvers allows the OPCAB surgeon to minimize the physiologic perturbations. One must avoid extremes of displacement to achieve a balance between visualization and stability.

Cardiac anatomical causes of hemodynamic instability during OPCAB

Hypotension may result from the following mechanical causes, which are listed in approximate order of frequency:

1 Compression of the right atrium and/or right ventricle against the right pericardium, right sternal edge, or right limb of the sternal retractor.

2 "Buckling" or "folding" of the right ventricular outflow tract due to excessive cephalad retraction of the heart, effectively producing RVOT obstruction, poor left ventricular filling, and subsequent hypotension. RVOT obstruction may also result from compression by the coronary stabilizer on the proximal LAD or diagonal or anterolateral OM territories.

3 Excessive compression by the coronary stabilizer on any left coronary territory with subsequent impaired filling and contraction of the left ventricle, resulting in hypotension.

4 Excessive traction with the cardiac positioning device for cardiac displacement, resulting in deformation of the longitudinal AV axis, creating or exacerbating mitral valve incompetence with resulting moderate/severe mitral regurgitation and subsequent hemodynamic deterioration [14].

5 Kinking of superior or inferior vena cava or pulmonary veins with resultant impaired right or left heart preload filling.

6 Regional myocardial ischemia during coronary occlusion for distal anastomoses, especially when a collateralizing artery is grafted, during which both collateralizing and collateralized territories are ischemic.

With apical suction device and long axis pull (Figure 17.5), there is less deformation of the anterior leaflet of the mitral valve that hangs off the cardiac skeleton between the right and left fibrous trigones. The posterior leaflet is folded. With DPS and gauze pad displacement alone, both the leaflets buckle [15].

The OPCAB surgeon should be cognizant of these cardiac deformations and scrupulously avoid entering into a vicious cycle of poor cardiac output, hypotension, acute mitral regurgitation, rising pulmonary pressures, and subsequent myocardial ischemia.

Steep Trendelenburg positioning allows better exposure of lateral and inferior walls and helps to miminize the distortion of the actual long axis. It can also "autotransfuse" over 2 L of blood into the central circulation more rapidly than any intravenous tubing and without the later risk of volume overload.

Other maneuvers for improved hemodynamic stability in OPCAB

Optimize afterload with small boluses of alpha agents (Phenylephrine, Norepinephrine). It is important to realize that this is only a temporizing measure and that it may achieve normal blood pressure levels in spite of ongoing low cardiac output. Prolonged use of alpha agents in the absence of adequate preload can be particularly detrimental and cause mesenteric and renal ischemia.

Optimize contractility. Use Milrinone load (150 μg Intravenous) and intravenous infusion (0.5 μg/kg/min) with Norepinephrine titration to maintain adequate afterload.

Pacing. The goal is a steady, regular rate of 80–90 beats/min. This reduces the time for diastolic filling and makes the heart smaller, improving lateral wall visualization, especially in the setting of cardiomegaly. Conversely, bradycardia increases diastolic filling time, distends the heart chambers, impairs visualization and may ultimately result in hypotension during cardiac displacement. Pacing is accomplished with careful, temporary placement of "alligator" clips on the right or left atrial appendage. The left atrial appendage may be more accessible during exposure of the circumflex coronary territory, when the right appendage may be less accessible. Pacing clips will "ground out" if submerged in blood within the pericardial space.

Insertion of IABP to augment coronary flow. Patients with very poor ventricular function will benefit from IABP counterpulsation during OPCAB. In the absence of severe peripheral vascular disease, IABP placement may be safely accomplished in the operating room. Patients with IABP placed preoperatively should have the device left in place through surgery. Frequently, the IABP may be removed soon after surgical revascularization.

An understanding of the coronary arteriogram and careful operative planning should avoid unanticipated myocardial ischemia. A coronary shunt should be used for any target vessel whose occlusion during grafting is expected to cause significant ischemia, thus avoiding instability. If critical regional myocardial ischemia does occur, the OPCAB surgeon should promptly insert a coronary shunt, release all traction and put the heart down for a period of time adequate to allow recovery of hemodynamic stability. Proximal anastomoses may be performed in the meanwhile.

Initiate CPB if prolonged hypotension that does not respond to the above maneuvers occurs. One should initiate CPB electively, before the onset of cardiac arrest. Conversion during/after cardiac arrest has high morbidity and mortality and should be avoided. CPB may also be electively initiated if unstable ischemic arrhythmias develop.

Specific problems during OPCAB

Ischemic ST changes

The OPCAB surgeon should be vigilant and be able to identify ischemia by watching the local myocardial color (dark red, dusky, or purple is

ominous), contractility, ECG (rhythm, ST elevations/inversions), BP, and PA pressure tracings. One should be able to process this logically with the knowledge of the angiogram and determine if ischemia is due to occlusion of the target artery's immediate territory or the territory of another artery that it being deprived of collaterals from the target artery. Such a situation might be the scenario of bradycardia and ST elevations in the inferior leads occurring when the LAD is grafted in the setting of total occlusion of the main RCA with left to right LAD–RCA collaterals. Either grafting and reperfusing the RCA territory first or using an intracoronary shunt during LAD grafting will avoid this pitfall.

It is also equally important to identify "pseudo-ischemia" ECG changes that may occur during vigorous displacement and/or rotation of the heart with altered surface lead pattern. In such situations, there may be an altered ECG pattern in the absence of the ominous myocardial and hemodynamic signs described above.

True ischemia is dealt with by the insertion of an intracoronary shunt and the increase of mean systemic pressure with volume and alpha agents. If it persists the heart should be transiently returned into the pericardial well, and the insertion of IABP considered. If the situation does not resolve one should consider going on bypass. TEE at this point will help provide an explanation of the compromise. Ischemic mitral regurgitation (MR) tends to propagate the downward spiral.

Atrial fibrillation

Distal anastomosis in atrial fibrillation is more difficult because systole is unpredictable and denies the surgeon a reliable rhythm with which to coordinate his movements. New atrial fibrillation occurring during OPCAB should be cardioverted. This should also improve the hemodynamics, particularly if the atrial fibrillation was associated with a rapid ventricular response.

Premature ventricular complexes

Premature ventricular contractions, couplets, and nonsustained runs of ventricular tachycardia suggest ischemia, and should always be taken very seriously. One should institute all measures described with ECG ischemia above. One should give a loading dose of amiodarone and/or lidocaine. One should also give a "pump dose" of heparin if only "half dose" was given for OPCAB. Also correct any electrolyte, hematocrit, acid-base, and ventilation/oxygenation abnormalities. If the ischemic arrhythmias persist, CPB should be initiated without delay, before cardiovascular collapse occurs.

Ventricular tachycardia/ventricular fibrillation, cardiac arrest, and emergency conversion

Sustained ventricular tachycardia, ventricular fibrillation, or cardiac arrest constitute an absolute indication for conversion to CPB. One should stop work on any anastomosis, insert a shunt, release all tractions, and perform emergent internal, nonsynchronized cardioversion. In the setting of full arrest the full

dose heparin may be most expeditiously given by sterile syringe directly into the aorta. If required, initiate internal cardiac massage to maintain adequate output, circulate inotropic drugs, and heparin. It is important to perform the massage with care not to injure the grafts previously performed.

Insert the aortic and right atrial cannula during brief pauses in internal compressions; this may be done most expeditiously without purse-string sutures if skilled assistance is available. The assistant should concentrate only on holding and securing the cannulae in place while the surgeon connects the lines and initiates CPB. Purse-strings can then be placed to secure the cannulae. The OPCAB surgeon may elect to do on-pump beating-heart CABG without global cardiac arrest after successful cardiac decompression and defibrillation.

In the case of immediate return of normal sinus rhythm and hemodynamic stability after prompt internal defibrillation, a very experienced OPCAB surgeon may choose to insert an intracoronary shunt and continue the operation off-pump, if the cause of the brief fibrillation is clearly apparent and a revised grafting strategy can reliably avoid its recurrence. Performance of proximal anastomoses may reperfuse grafted myocardium, limit regional myocardial ischemia, and improve hemodynamic stability during subsequent distal anastomoses.

Transesophageal echocardiography is useful to detect impending hemodynamic crises. It can also aid to assess the effects of cardiac positioning on ventricular and valvular function. Reaping the benefit of this technology requires clear and constant communication between surgeon and anesthesiologist.

Operative set-up for the distal anastomosis

The positioning of the heart with pericardial sutures and suction-based cardiac positioning device (Starfish) was detailed earlier. In applying the coronary-stabilizing device (Octopus), we place the U-bend headlink distally (at the "toe" end of the anastomosis) along the coronary vessel. We occlude only the coronary proximally (heel end) as follows:

1 Silastic tapes ("Retract-o-tape", Quest Medical Inc., Texas, USA) looped twice around the target artery 1–2 cm proximal to the planned arteriotomy. This silastic tape has two significant advantages over other suture materials for the purpose of temporary coronary occlusion. The tape is of an air-cushioned hollow silicon tube construction. Its blunt-tipped needle together with the width and soft pliability of the tape construction reduces the likelihood of coronary trauma. Polypropylene or other nondistensible suture materials are never used for this purpose. Moreover, no occlusion of any kind is routinely applied distal to the site of the planned anastomosis to eliminate risk of iatrogenic coronary injury distal to the new bypass graft.

After positioning the loop, it should not be tightened. The initial arteriotomy is more safely and easily made with a very fine coronary "beaver" knife in a pressurized coronary artery, minimizing risk of injury to the back

wall of the vessel. Thereafter, the loop is tightened only enough to eliminate antegrade bleeding from the arteriotomy.

2 When occluding the PDA and posterolateral LV branch of the RCA, it is useful to direct the axis of traction of the silastic loop downward into the pericardial well. Simple traction of the loop toward the sternal retractor or skin will direct the tape upward and interfere with the surgeon's access to the heel of the PDA. Hence, we place a silk suture on the diaphragm below the level of the heel of the PDA, then pass the silastic tapes through the loop of silk suture and finally secure the silk with a ligaclip to create the "pulley." Pulling the silastic tape downward in this more appropriate axis facilitates unimpeded access to the coronary target.

If the silastic loop fails to provide a satisfactory bloodless field due to persistent antegrade flow, it should be suspected that the silastic loop did not in fact pass around the coronary artery—usually because of an unsuspected deviation in the course of the artery within myocardium or epicardial fat. Severe coronary calcification may prevent occlusion of flow by a silastic loop. Retrograde flow from collaterals—especially if just grafted with abundant new inflow—may also be problematic. In these cases, an intracoronary shunt may be inserted to establish a satisfactory operative field. Only very rarely is a loop placed around the coronary artery distal to the anastomosis; when this is necessary, the silastic is tightened especially judiciously.

Intracoronary shunt

Temporary coronary shunts are inserted through the arteriotomy, maintaining to an extent the perfusion of the territory. The driving pressure through an intracoronary shunt is passive coronary perfusion pressure and linked to systemic pressure. According to the Hagen–Poisseuille equation, flow rates are proportional to the perfusion pressure and the fourth power of the internal radius of the shunt. The internal diameter of a shunt is less than the product size that corresponds to its outer diameter. Flows through shunts are therefore 50% of the native flows at best. Effective flow and coronary perfusion are probably not achievable with shunts smaller than 1.5 mm and they probably are more hemostatic than anything else.

Commercially available shunts range in diameter from 1.0 to 3.0 mm and in 0.25 mm increments. They are deformable and have an attached tether that facilitates removal after the anastomosis is completed and before the sutures are tied down. Though shunts may limit the ischemia associated with temporary occlusion of a coronary artery, their presence in the anastomosis is a mechanical impediment to suturing that requires an adjustment on the part of the surgeon. However, some OPCAB surgeons feel that an intracoronary shunt may serve to prevent inadvertent suture bites through the back wall of the target coronary artery and may prefer to use these shunts routinely. While coronary shunts have been shown to cause some degree of endothelial damage in the coronary artery, the clinical impact is uncertain [16, 17].

At Emory we use shunting very selectively:
1 If there is evidence of myocardial ischemia upon temporary occlusion of the coronary artery (ST segment elevations > 2 mm, elevation of PA pressures, and associated with systemic hypotension, ventricular arrhythmias, or atrial bradyarrythmia upon occlusion of the RCA).
2 If there is low-grade (60–70%) stenosis of a large coronary, especially the RCA. Occlusion of such an artery would result in significant ischemia in its territory as collateral circulation would not have adequately developed. An interval of test occlusion of 2–5 minutes can be used prior to the arteriotomy to give an indication of the anticipated compromise.
3 If the artery to be occluded supplies a large territory either directly or through collaterals. Ideally dealing with the distal and proximal anastomosis of the collateralized vessel graft should limit the compromise resulting from occlusion of this feeding vessel.
4 If the target coronary artery is very calcified, preventing effective occlusion by the elastic tape.
5 Intramyocardial vessels where placement of deeper silastic loop may be dangerous and invite the risk of ventricular cavity penetration.

An essential tool for every OPCAB operation is the Blower/Mister (Medtronic ClearView, Minnesota, USA). This is a device that delivers a jet of CO_2 under pressure in the middle of a jet of pH-balanced saline solution. The resulting stream of mist and CO_2, when directed over the arteriotomy, predictably and effectively clears the blood, usually coming retrograde at the toe end of the coronary arteriotomy. There is no risk of air embolism as the CO_2 is rapidly reabsorbed. The second assistant must learn to effectively use the blower mister. In addition to clearing the blood at the point of anastomosis, it should be directed in such a manner that it blows open the walls of the vessel to give the surgeon clear view of the intimal edges for suture placement. The blower should be directed at the coronary only at the time of stitch placement to minimize the risk of intimal endothelial injury.

Construction of the distal anastomosis

For virtually all left-sided coronary artery targets, the operating table should be rotated to the right to bring the coronary to a more anterior and horizontal plane. For PDA targets, a steep Trendelenburg position will help. For the PDA anastomosis, the second assistant with the blower mister should stand to the cephalad end on the right side of the table while the surgeon should stand toward the caudal end on the right side of the table. This will give the surgeon a better view of the inferior surface of the heart with better needle angles. All these will translate to a superior quality of the anastomosis.

If set up correctly, the surgeon now should adhere to two golden principles:
"See every stitch, See the intima, See the lumen"
"Roll and advance the needle along its curve"

Avoid pushing and "fork-lifting" and hanging the coronary wall off the needle. This leads to vessel injury.

We perform all distal anastomoses using running 8-0 prolene suture. Calcific coronaries will need a stronger 7-0 suture needle. Sutures are placed in exactly the same pattern for each coronary artery target as is preferred for the surgeon when performing on-pump coronary artery bypass grafting—the only difference is the avoidance of CPB. After completion of each anastomosis, it is allowed to bleed through to expel air, prior to tying down the suture. The conduit should be occluded with an atraumatic vascular clamp to prevent retrograde bleeding and loss of coronary perfusion pressure. Inadvertent flushing of air down the distal coronary can result in air embolism and can cause significant hemodynamic instability. The position of the atraumatic vascular clamp on each vein graft should be as close to the aortic end of the graft as has been de-aired by back-bleeding. This distance is determined by the location of venous valves. These small clamps will be removed after final de-airing of conduits after the proximal anastomoses are completed.

Construction of roximal anastomosis

The deeper pericardial sutures are released. The pericardial sutures on the right and left side of the aorta are tightened to expose the aorta. Reverse Trendelenburg and modest use of vasodilators should provide a systolic pressure of 90–100 mm Hg to allow the application of the side-biting clamp. The clamp should not occlude too much of the aorta to avoid a drop in cardiac output.

Proximal anastomoses may be constructed before or after all distal anastomoses, as per surgeon preference. Judging ideal graft length is easier when proximal anastomoses are performed after distal anastomoses.

Clampless beating heart surgery

When the aortic atheroma burden is significant, precluding the application of a side-biting clamp, the aorta can still be used for proximal anastomoses utilizing the soft spots on its anterior wall by alternative means. We use the HEARTSTRING II Proximal Seal System (Guidant/Boston Scientific, USA). The HEARTSTRING device has a proprietary aortic hole cutter, and deploys a hemostatic coiled umbrella-shaped seal underneath the punch hole. The anastomosis is then hand sewn with a 1/2 radius needle on a 6-0 prolene suture as opposed to the usual 3/8 proximal needle. The deeper curve allows one to avoid inadvertently catching and stitching in the umbrella of the device to the anastomosis. Not advancing the needle gently along its curve will exert pressure against the aortic wall to disrupt the seal of the umbrella against the aortic wall and lead to significant blood in the field. Before the suture is tied, the leading edge of the umbrella is pulled gently to uncoil and remove the device. There is no metallic component in this anastomosis and is akin to conventional anastomosis [18, 19].

At the end of the proximal anastomoses suture placement, correct de-airing procedure is important to prevent coronary or cerebral air embolism. The suture should be loosened at its end, the aortic side clamp released, the aorta allowed to de-air, and bleed for a couple of ejections through the anastomoses. Then the suture is pulled up, tightened and tied down. At this point the conduit still has the bulldog clamp on it. The conduit with venous valves that may not have completely backfilled is then again de-aired with a 26-gauge needle and the bulldog then removed to complete the de-airing process.

Strategies for complex risk factors

1 *Tight left main coronary artery disease.* Elevation of the heart to place a deep pericardial traction suture can result in significant hemodynamic instability and even cardiac arrest. Hence, initial manipulation of the heart should be minimized and the left IMA to LAD anastomosis should be performed first, generally with an intracoronary shunt. The heart should be elevated to place a deep traction suture only after reestablishing flow to the anterior wall. Placement of an IABP is another option.

2 *Severe obstruction of multiple coronaries.* These cases may be demanding. IABP may be inserted at the beginning of the case. The proximal anastomoses are constructed first. Here, it is vital to accurately judge the correct length of vein segments as they will all have to be cut before distal anastomosis. A silk suture can be used to judge the distal to proximal length needed. The most severe stenosis is dealt with first.

Grafting with multiple in situ internal mammary artery/composite arterial conduits will also provide coronary inflow immediately after completion of distal anastomoses.

3 *Intramyocardial coronaries.* The same strategies and techniques are used to locate and expose intramyocardial coronary arteries on- and off-pump. Patient use of the coronary stabilizer and mister-blower devices will allow the experienced OPCAB surgeon to graft virtually any intramyocardial vessel. However, special care must be exercised to avoid violation of the ventricular cavity during placement of the silastic snare for occlusion of very deeply intramyocardial coronary arteries.

The Medi-Stim flow probe can also be used to locate the position of the buried coronary artery. Occasionally, CPB may be necessary to facilitate coronary localization and exposure on a decompressed heart.

4 *Coronary endarterectomy.* An endarterectomy usually requires an extended arteriotomy and consequently much longer coronary occlusion for anastomosis. Many times, due to extensive calcifications the occlusion must be performed very proximally and the use of shunts is not possible. Extensive coronary endarterectomy is generally very well tolerated off-pump in cases of complete chronic coronary occlusion. However, significant regional myocardial ischemia and subsequent hemodynamic instability may result from prolonged endarterectomy of patent, diseased coronary artery targets.

5 *Poor left ventricular function and cardiomegaly.* Prophylactic loading and continuous infusion of milrinone and insertion of an intraaortic balloon pump prior to cardiac manipulation can allow completion of the distal anastomoses safely in many patients with low LVEF. When exaggerated cardiac manipulation cannot be tolerated, OPCAB with CPB without cardioplegic arrest can decompress the heart and allow construction of the distal anastomosis on the warm heart. Avoidance of cold cardioplegic arrest avoids global myocardial ischemia and limits myocardial edema and subsequent deterioration of ventricular function. However, the cumulative effects of sequential coronary occlusion and ischemic times for construction of distal anastomoses can lead to ventricular dysfunction and a downward spiral of perfusion unless all appropriate OPCAB strategies and techniques are employed.
6 *Ischemic MR.* If there is no structural abnormality with the valve apparatus, MR could be the result of papillary muscle or inferior wall ischemia. Patients with moderate MR may not tolerate displacement of the heart as it may be associated with worsening of the MR. However, in many cases of moderate functional MR, in expert hands OPCAB may be attempted and may result in postrevascularization improvement in MR and obviate the need for mitral valve surgery.
7 *Redo-OPCAB.* Reoperative OPCAB is feasible for experienced surgeons in approximately half of all cases. Cases requiring lateral wall grafts in the setting of a patent in situ left IMA graft that tethers the heart and limits rightward displacement of the heart are particularly challenging and may be more safely performed with the use of CPB.

Absolute contraindications to OPCAB

1 Cardiogenic shock or cardiac arrest
2 Ischemic arrthymias
3 Anatomic factors preventing dislocation of the heart.
  (a) Left pneumonectomy
  (b) Severe pectus excavatum

Postoperative care

It is important to remember the following intraoperative issues that have a definite impact on the postoperative course.
1 *Bleeding and coagulation.* Avoidance of CPB does not automatically translate into less coagulation disturbances postoperatively. As alluded to earlier, it is vital to pay close attention to minimize bleeding and cell saver salvage at every stage of the operation. If the patient receives more than three cell saver retransfusions, it sets the stage for significant coagulopathy postoperatively and increased risk of bleeding.
2 *Intraoperative hypotension*. OPCAB, by avoiding CPB and its inflammatory response, holds the promise of minimizing end-organ insults. However, if

executed imperfectly, OPCAB can lead to periods of significant hypotension and myocardial ischemia. Intraoperative hypotension can lead to stroke and renal failure. Pulmonary venous congestion may occur from acute MR. A rise in LV end-diastolic pressure from ischemia can lead to pulmonary congestion and edema and prolonged intubation.

As a rule of thumb, the mean arterial pressures should be maintained in the normal or near-normal range, never less than 60 mm Hg, to avoid organ malperfusion.

3 *Intraoperative myocardial ischemia*. We have detailed the mechanism of the occurrence of myocardial compromise from inappropriate OPCAB grafting strategy. If not effectively dealt with, this could lead to increased inotrope requirement postoperatively. Swan Ganz catheter and transesophageal echocardiography are invaluable in optimization of hemodynamic parameters.

4 *Graft flows and postoperative ECG changes*. New ECG changes postgrafting, either intra or postoperatively, are alarming. If the technical principles described above are adhered to, anastomotic patency should be reliable. Though not routinely used, intraoperative assessment of graft flows can confirm patency and simplify the interpretation of new postgraft ECG changes. More accurate than Doppler, we use the transit-time ultrasound-based technology of Medi-Stim^{R} (Oslo, Norway) to provide the mean coronary flows, diastolic filling percentage (DF), and the pulsatility index (PI). The echocardiogram revealing a new regional wall motion abnormality in the completely revascularized patient will herald the prompt use of coronary vasodilator agents. An individualized assessment, warranted by the clinical condition and coronary substrate of the patient, directs the extent of early postoperative intervention.

5 *Aspirin and Clopidogrel*. OPCAB maybe associated with more normal platelet function and an incidence of a hypercoagulable state. The detrimental effects may also be increased in coronary endothelial injury associated with use of intracoronary shunts. At Emory, all patients are routinely given 600 mg ASA per rectum after induction of anesthesia. Clopidogrel (150 mg orally) is given 4 hours postoperatively if the mediastinal blood loss is less than 100 cc/h for 4 hours. They are then continued on ASA 81 mg and Clopidogrel 75 mg once daily orally starting the morning after surgery. We have found no increased incidence of mediastinal blood loss with this protocol [20].

6 *Postoperative pain*. We routinely use soft four-channel Blake (Ethicon, NJ, USA) drains for mediastinal drainage. We and others have found that these drains are just as effective as larger and rigid drains, and are better tolerated by patients [21]. We do not use epidural anesthesia for OPCAB.

Conclusion

OPCAB surgery demands adherence to several strategic and technical principles. When these are followed diligently, OPCAB is a reproducible and reliable technical exercise associated with numerous documented benefits to coronary patients.

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CHAPTER 18

Valvular Operations

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Introduction and overview

To avoid surgical complications, operations involving the cardiac valves require a detailed understanding of *cardiac anatomy* and a *gentleness of technique*. These two concepts are the keys to uneventful valve operation. In each subsection, we first present the relevant surgical anatomy for each cardiac valve. The anatomic approach to operation for that particular valve is then addressed with a particular emphasis to the correction of its pathology. Potential complications are then described at the time point during operation when adverse events may occur. We do not address prosthetic valve endocarditis or thrombosis, two areas that have been extensively covered in the literature.

Aortic valve

Anatomy

The aortic valve is a trileaflet structure that separates the left ventricle from the aorta [Figure 18.1]. The valve is composed of three leaflets (or cusps)—the left, right, and noncoronary—that are attached to the aortic wall at the fibrous annulus. Dilatations of the aortic root, called the sinuses of Valsalva, are found immediately adjacent to each leaflet. Three commissures are formed from the apposition of each cusp to one another on the fibrous annulus and separate the cusps from each other. The two main coronary ostia arise from the left and right sinuses of Valsalva. Below the commissure between the right and noncoronary cusps lies the membranous septum, through which the bundle of His travels. The anterior leaflet of the mitral valve is in direct fibrous continuity with the commissure and annulus between the left and noncoronary cusps.

Approach/incision

The traditional approach to aortic valve operation is via a median sternotomy. Several alternative approaches have been described recently, including a

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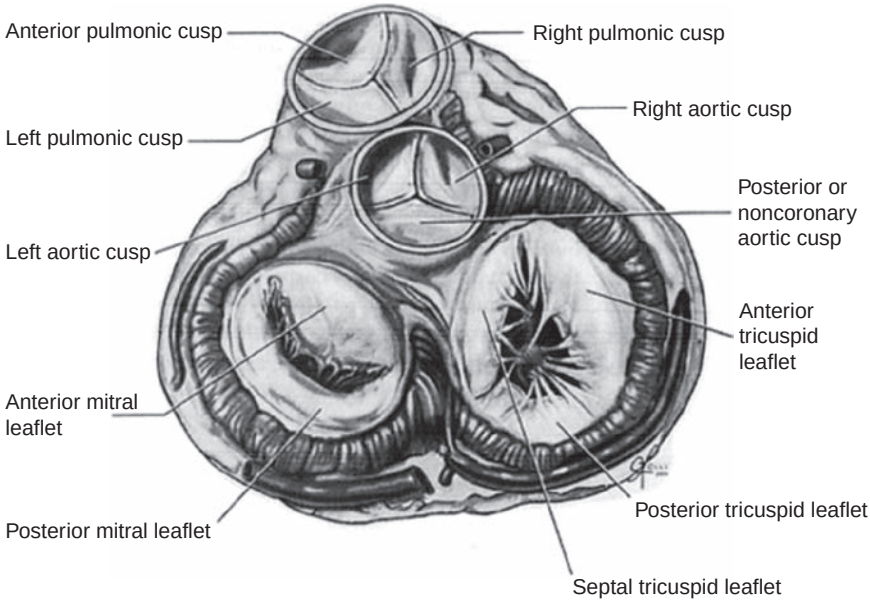

Figure 18.1 Anatomic relationship between the aortic valve and surrounding structures.

number of minimally invasive options [1–3]. Each incision offers potential advantages, but the most common approach remains the full median sternotomy.

A low transverse or oblique aortotomy is typically utilized to access the aortic valve. *When manipulating the aorta, areas of calcification should always be identified and avoided.* Incising and manipulating calcified areas of the aorta increases the risk of embolization and subsequent stroke. Aortic dissection is also a potential risk with a calcified aorta whenever the cross-clamp is either applied or removed.

Calcification of the aorta should be identified by palpation and epiaortic ultrasound and avoided whenever possible. The key to uneventful aortic surgery is to treat the aorta as gently as possible.

Despite attempts at avoiding these areas, sometimes incising calcified aorta is necessary. A local endarterectomy and debridement may then be required for successful closure of the aortotomy; in these instances, only adventitia may be left. In the situation of heavy, diffuse aortic calcification or the "lead pipe" aorta, the safest option is peripheral cannulation via the femoral or axillary artery. If one is required to clamp a focal area of calcification, an attempt should be made to clamp the calcification such that the clamp does not fracture the plaque by placing the clamp so that it compresses the plaque in its long axis. If clamping is impossible, then a reasonable alternative is deep hypothermia and circulatory arrest without aortic cross-clamping [4]. Another option is replacement of the ascending aorta itself. In either case, the

transverse aortotomy is made in a soft portion, if possible, of the aorta 10–20 mm above the right coronary ostium.

For the oblique aortotomy, the incision is started higher up on the medial aspect of the aorta near the fat stripe and continued downward toward the noncoronary sinus, leaving at least 10 mm between the lower limit of the incision and the aortic annulus. Extension of the incision beyond this point will lead to difficulty in closing the aorta. A retractor can be used to help extend the incision under direct vision, but the utmost care must be taken with retraction as the aortic wall is often thinned and dilated, especially in elderly female patients, thus predisposing them to accidental tearing. In patients with poststenotic dilatation, the aorta is often very thin. Great care and gentleness should be used in this circumstance in any manipulation of the aorta, from the purse-string placement to aortic cross-clamping to the aortotomy closure.

Valve excision

The native aortic valve is excised with scissors or a knife. One should leave at least a 1–2-mm margin of tissue at the annulus. Excising too much native valve tissue can lead to an unexpected disruption and gap in the aortic annulus. *Thus, it is always preferable to leave tissue behind that can be trimmed later if needed.* Most patients will have calcifications in and around the annulus. These areas are individually crushed and sharply debrided using clamps or pituitary rongeurs, being careful to avoid tugging too aggressively—this can perforate the annulus. Pieces of calcium falling into the left ventricular cavity pose a potential danger since they can embolize and cause a stroke. As a precaution, a moist-folded sponge can be placed in the left ventricle before attempting debridement of calcium. Any loose calcium particles will fall onto the sponge, and copious irrigation of the left ventricle, annulus, and ascending aorta with cold saline before removal of the sponge will help clear the area of any debris. During the debridement itself, if the assistant aggressively suctions the fragmented particles as well as the debrided area itself, a great deal of these fragments can be removed prophylactically.

Vigorous debridement of annular calcifications may be carried out safely using the above technique. The cardiac surgeon must develop his or her tactile sense to avoid pulling too hard and ripping the aorta. Particular attention should be paid to this possibility. The correct technique is to use the rongeurs to first crush calcifications to weaken them and then fracture or cut the calcium off the annulus. Any local tears into the media or adventitia may be repaired by incorporating the tears in the pledgeted, multifilament mattress stitches used to secure the aortic prosthesis.

Injury to the anterior mitral valve leaflet is possible during the annular debridement, given the fibrous continuity with portions of the noncoronary and left coronary annuli. If the anterior leaflet is partially detached or disrupted, repair may be performed by incorporating the tears with the pledgeted sutures (used to secure the aortic prosthesis) brought from below the annulus.

Prosthesis placement

The prosthesis should be carefully sized to ensure optimal hemodynamics without causing undue disruption or distortion of the aortic annulus. Single sutures placed through each commissure can be used to raise the aortic orifice up for better visualization. The appropriate prosthesis is the largest one that fits the annulus "comfortably." Oversizing the prosthesis can lead to disastrous or lethal results. If the prosthesis is too large, closure of the aortotomy is difficult and the coronary ostia or arteries may be distorted and compromised. This may lead to a large perioperative myocardial infarction; worse still, it may lead to cardiac arrest and subsequent death.

Interrupted, horizontal mattress stitches with pledgeted 2-0 Ethibond or Ticron are the best material to secure the prosthesis. Pledgets create a more equal distribution of pressure on the suture line and are critical in evenly spreading out tension in the annulus. The more even and uniform the tension is, the less likelihood of tearing. Weaker and more fragile aortic tissue is an absolute indication for the use of pledgets. Solid bites must be taken through the annulus. With every suture placement, the surgeon should reassess for any excess calcium present. Excess calcium will not hold sutures and leads to an insecure prosthesis and paravalvular leaks. If necessary, further debridement should be undertaken during suture placement.

During placement of sutures, injury to conduction tissue and the coronary arteries may occur. Deeply placed sutures along the right and noncoronary commissure near the membranous septum can injure the underlying conduction tissue, resulting in various forms of heart block. Occasionally, complete heart block does occur, necessitating placement of a permanent pacemaker. Sutures that are placed too deep along the left coronary annulus may injure the left main coronary artery that runs along the posterior aspect of the aortic root. This may happen to the right coronary artery as well. Injury to the coronary arteries is a disaster and requires rapid identification, repair, and appropriate revascularization or reconstruction with saphenous vein grafts.

It is important to seat the valve at the lowest point of each annulus. When tying the sutures, the direction of knot tying must be parallel to the curvature of the ring rather than across the leaflets. Tying should also be performed parallel to the suture ring. Otherwise, the prosthetic valve may be damaged by contact with the suture or the surgeon's finger. The coronary ostia should be visualized after seating of the prosthesis to ensure that ostia are free of any obstruction. If necessary, some types of prosthesis can be rotated to prevent blockage of the coronary arteries. Finally, for a mechanical prosthesis, the surgeon must verify that the valve is functioning properly with unrestricted leaflet movement. If a mechanical leaflet is obstructed, the valve must be rotated or a new prosthesis placed. *Bileaflet mechanical valves should be oriented perpendicular to the septum; this minimizes the occurrence of subvalvular interference with the mechanical leaflets. Trileaflet bioprosthetic valves should be oriented with the struts aligned with the commissures; this minimizes obstruction of the coronary ostia.* Noneverting sutures should be used for bioprosthetic valves because that is the most secure stitch; however, with mechanical valves,

everting stitches should be used to push the prosthesis into the middle of the aorta and help avoid subvalvular interference with the leaflets.

Small aortic root

The small aortic root presents a particular challenge when performing aortic valve replacement. Placement of a prosthesis that is too small will leave the patient with patient–prosthesis mismatch [5]. Too large a prosthesis, as noted above, can disrupt the annulus, and can cause injury and tearing of the aorta. These complications are best avoided by ensuring that the largest prosthesis that correctly fits the patient is selected.

When a root enlargement procedure is required because the root is simply too small to safely fit the smallest acceptable valve; the technique of choice depends on surgeon experience and patient-specific requirements. The most commonly used methods are to extend the aortotomy to either the midpoint of the noncoronary annulus (Nicks procedure) or down the commissure between the noncoronary and left coronary cusps (Manouguian procedure) [6–8]. A patch of Dacron or Gore-Tex is then sutured into the incision to help close the aortotomy, thereby enlarging the aortic root. The patch must be securely sutured in place particularly below the prosthesis, as significant bleeding that is difficult to control can occur after removal of the cross-clamp.

Aortotomy closure

Closure of healthy aorta can be achieved with a single running monofilament suture. However, we recommend closure with a double layer of monofilament suture. Reinforcement of the aortotomy with pledgeted sutures, Dacron, or strips of pericardium may be performed if the tissue is particularly thin or friable. *The keys to successful aortic closure are even, large (3–4 mm) bites on each side of the aortotomy in which the curve of the needle is religiously followed. Tension must be maintained on the stitch until the suture line is tied.* Our preferred stitch is 4-0 Prolene on a BB needle. Bleeding from the suture line may nonetheless occur after aortotomy closure. Control of systemic blood pressure during closure of the aortotomy and during the immediate postoperative period is critical to prevent this complication. If bleeding from the suture line occurs, it is more easily addressed while still on cardiopulmonary bypass when it is possible to readily decrease aortic flow and aortic pressure. If cardiopulmonary bypass has been discontinued, then temporary clamping of the superior vena cava will reduce aortic flow sufficiently to allow repair of bleeding sites. It is imperative that any repair be performed when pressure in the aorta has been reduced; attempts at repairing a friable aorta while it is fully pressurized will usually lead to worsening of the bleeding and further injury to the vessel. Repairs are best performed with 4-0 horizontal mattress sutures, interrupted and pledgeted.

Postoperative complications

Low cardiac output syndrome or perioperative myocardial infarction after aortic valve replacement is often caused by inadequate myocardial protection.

With critical aortic stenosis, significant hypertrophy is often present. Such hearts often require larger doses of cardioplegia to adequately protect them. Even with antegrade delivery, the subendocardium is vulnerable because of such hypertrophy. Retrograde delivery is a very useful adjunct to ensure adequate delivery of cardioplegia to all areas of a hypertrophied heart. Whatever the delivery method, it is important to give an adequate amount. With the situation of severe aortic insufficiency, one must be careful to prevent left ventricular distention before the cross-clamp is applied. In the case of severe aortic insufficiency, it impossible to arrest the heart by giving cardioplegia in the aortic root. Cardioplegia should be given directly down the ostia after clamping and incising the aorta. Retrograde cardioplegia is very useful in this circumstance as well.

Paravalvular leak in the absence of concomitant endocarditis is a rare complication. The reported incidence in the literature ranges from <1% to 2%, and seems to be independent of the type of prosthetic valve implanted. Technical errors are responsible. These include inappropriately large gaps between sutures and inadequate decalcification. In a symptomatic patient, early reoperation is recommended as rapid deterioration can occur if left untreated. In most cases, the leak can be repaired with simple pledgeted sutures. In the asymptomatic patient with a small leak, close monitoring is a reasonable approach with the caveat that any clinical deterioration or ventricular dilatation warrants reoperation.

Currently available mechanical prostheses are extremely durable and resistant to structural deterioration. Freedom from reoperation for current mechanical valves exceeds 95% at 10 years and 90% at 15 years [9–15]. On the other hand, structural deterioration is the most common nonfatal valve-related complication in bioprosthetic valves. Long-term studies of first- and second-generation aortic bioprosthetic valves demonstrate that the vast majority (>90%) of these devices remain structurally intact for approximately 12 years [16–18]. Other studies show that freedom from reoperation is greater than 90% at 10 years but less than 70% at 15 years, suggesting that the life span of such valves is within this time period [17–25]. Premature bioprosthetic valve dysfunction seems to occur with greater frequency in younger patients, particularly those under 40 years of age, presumably due to increased hemodynamic stress placed on the valve when compared with the elderly. There is increasing evidence that hypercholerstolemia may contribute to early bioprosthetic structural deterioration [26]; for this reason, we routinely place all recipients of bioprosthetic valves on statin agents.

Mitral valve

Anatomy

The bileaflet mitral valve is one of the most complex structures of the human heart. The two leaflets, the anterior and posterior, are attached to the mitral annulus and to the papillary muscles (via primary and secondary chordae)

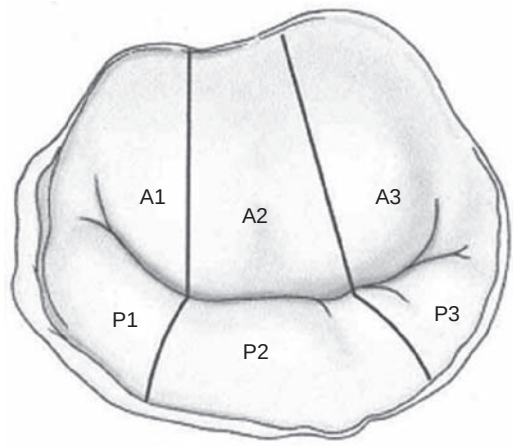

Figure 18.2 The conventional terminology used to describe the pathoanatomic parts of the anterior and posterior leaflets of the mitral valve.

[Figure 18.2]. The anterior leaflet is in direct continuity with the left and noncoronary cusps of the aortic valve and is directly below the left ventricular outflow tract. It accounts for approximately one-third of the circumference of the annulus while the posterior leaflet arises from the remaining two-thirds. The annulus is part of the fibrous skeleton of the heart and occurs where the leaflets attach to the intersection of the left atrium and the ventricle. *The annulus itself is surrounded by vitally important structures that the cardiac surgeon must know and understand* for safe surgery: the left circumflex coronary artery, the coronary sinus, the aortic root, and the atrioventricular node [Figure 18.3]. Of critical importance are the right and left trigones.

Approach/incision

Although minimally invasive approaches have been described, a median sternotomy is still the most common incision for surgery on the mitral valve [2, 3, 27]. The mitral valve may be accessed through several approaches. The most common are Sondergaard's groove, transseptally, and the transatrial oblique approach. In the first, the right atrium is dissected off the left atrium and the left atrium is incised medial to the right pulmonary veins. This incision can be rather easily extended to the inferior vena cava. Extension in the opposite direction over the dome toward the aortic root must be performed with the closure in mind as too far an incision can make closure hazardous and difficult.

The transatrial oblique approach is useful when the left atrium is small or when adhesions are present that make dissection of the back of the heart precarious. The incision is made from the right superior pulmonary vein obliquely across the right atrial wall, and then extends across the interatrial septum just up to the limbus of the fossa ovalis. *The incision must not cross*

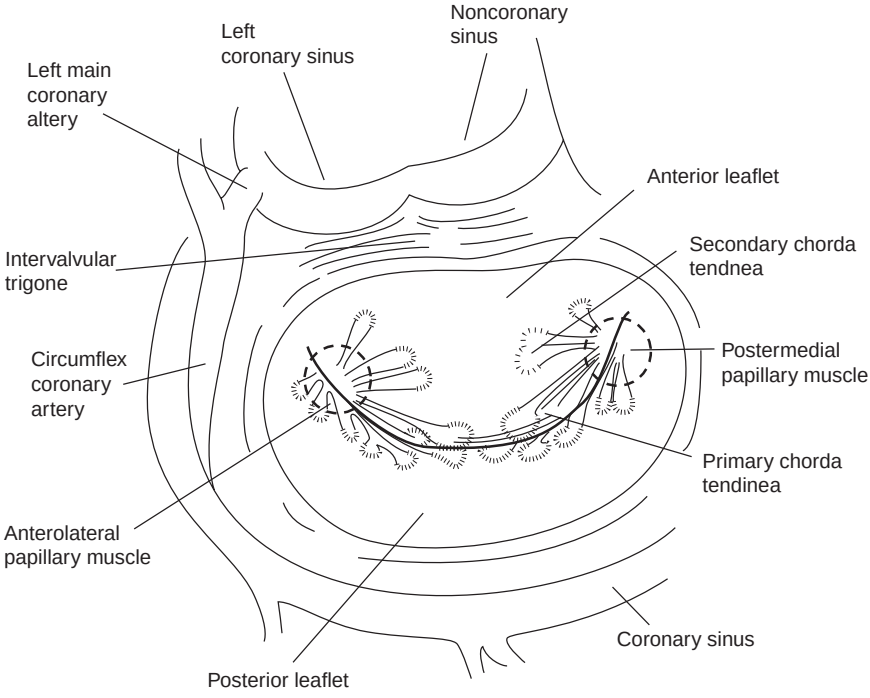

Figure 18.3 The mitral valve and critical structures that the cardiac surgeon must recognize, including the circumflex coronary artery, the coronary sinus, atrioventricular node, and aortic root. Note that the left and right trigones are superior to the commissures.

across the anterior limbus as this can injure the mitral valve annulus; any extension of the incision should be made inferiorly on the limbus to avoid such injury.

A transseptal approach can also provide excellent exposure of the mitral valve. The right atrium is opened to expose the fossa. A longitudinal incision is performed in the fossa and extended horizontally up to the superior vena cava. Again, the incision must avoid the anterior portion of the fossa ovalis as the mitral annulus is located just underneath.

Whatever the approach utilized, excessive retractor pull must be avoided as the atrium can be friable; the use of two small retractors rather than a single larger one can help prevent any unintended tears.

Mitral commissurotomy for mitral stenosis

Indicated for mitral stenosis, commissurotomy is incision of the commissures and possibly the papillary muscles to improve leaflet mobility. Complications include either residual mitral stenosis or new mitral regurgitation. Residual stenosis is often the result of the preexisting calcification in the subvalvular area or failure to properly reconstruct the mitral valve orifice. Any residual stenosis can be identified in the operating room prior to decannulation. The cardinal signs are high atrial pressure, low cardiac output, and

echocardiographic findings of mitral stenosis. Treatment of this complication is to extend the commissurotomy to the annulus or add an additional incision of the papillary muscles to free up the chordae. If neither can be accomplished successfully, then mitral valve replacement must be performed.

New or severe mitral regurgitation is almost always the result of excessive mitral commissurotomy and can be identified by high atrial pressures, a prominent V wave on the pressure tracing, and echocardiographic evidence of mitral regurgitation. The valve must be inspected to identify the site of regurgitation. If at the commissures, then a pledgeted annular U stitch can often repair the defect. If this is unsuccessful, then valve replacement must be performed.

Mitral valve repair for mitral regurgitation secondary to myxomatous disease

Myxomatous disease of the mitral valve produces redundant mitral valve tissue resulting in regurgitation because of failed leaflet coaptation. Failure of leaflet coaptation is secondary to excess tissue of the posterior leaflet as well as a distorted, enlarged annulus. Our repair strategy is to resect redundant portions of the posterior leaflet and perform simple posterior leaflet repairs, place an annuloplasty ring, and then reassess the degree of mitral regurgitation by saline injection into the left ventricle. By following this strategy, we estimate that over 90% of myxomatous valves can be successfully repaired. The most frequent complications of valve repair for regurgitation are residual mitral regurgitation, new mitral stenosis, left ventricular outflow tract obstruction, and dehiscence of the annular ring.

The goal of posterior leaflet resection is to provide an adequate coaptation line with the anterior leaflet and to reduce leaflet height, preventing systolic anterior motion (SAM) of the anterior leaflet resulting in left ventricular outflow tract obstruction. Specific techniques of posterior leaflet resection have been well documented previously [28].

Inadequate resection of a flail or redundant posterior leaflet will result in residual mitral regurgitation and also increase the risk for SAM. Conversely, too much resection will result in a gap in the coaptation line.

Generally, the overall goal of posterior leaflet surgery should be the produce a smooth curvilinear coaptation line with maximum leaflet height of approximately 1–1.5 cm. We do not advocate chordal shortening because evidence is mounting that additional rupture may occur after this technique [29]. The anterior leaflet itself should be treated with great respect and resection is rarely required. Should the anterior leaflet need to be repaired because of true prolapse, we recommend the specialized techniques of artificial chords with Gore-Tex or the edge-to-edge technique [30].

For myxomatous disease, an annuloplasty ring must *always* be placed. This is a fundamental concept of Carpentier and Duran [31, 32]. Sizing is critical. The annulus, after years of regurgitation with degenerative disease, is floppy. Conceptually, the annulus becomes too small for the anterior leaflet. Why? If floppy with redundant tissue, the annulus will not provide the relatively

stable skeleton necessary for the anterior leaflet to spread out fully and thus coapt at the correct line and in the correct plane with the posterior leaflet. Hence, the annuloplasty ring should be sized to the height of the anterior leaflet (*not* the trigones and *not* the commissures) and it should be *oversized*. A ring that is too small can lead to SAM because the redundant anterior leaflet tissue is now predisposed to obstruct the left ventricular outflow tract.

The complications to avoid during ring annuloplasty placement are circumflex artery compromise, atrioventricular dissociation, and dehiscence of the ring. Ring annuloplasty stitches should be placed parallel to the annulus, at the junction of the leaflet and the annulus. Radially oriented bites should be avoided because by definition they exert radial stresses and will pull to some extent on the circumflex artery, especially near P1 and P2. Bites should be placed deep with the needle entering the annulus, then into the LV muscle, and then coming out on the atrial side again. Of paramount importance is the requirement that the plane of the needle bite should be orthogonal to the annular plane. If this is the case, then it is impossible for the stitch to impinge or distort the circumflex artery. It is imperative that the two fibrous trigones are incorporated by the annuloplasty stitches, especially if C-shaped rings are used. Because the trigones are part of the structural skeleton of the heart, ring migration and dehiscence may occur with recurrent mitral regurgitation if the trigones are not used to firmly anchor the prosthesis.

Mitral valve repair for mitral regurgitation secondary to ischemic disease

For ischemic mitral regurgitation, the pathophysiology begins with ventricular dysfunction. As the ventricle dilates, it pulls the papillary muscles and mitral valve leaflets apart, leaving a gap in the coaptation line. Mitral regurgitation then occurs. The gap frequently occurs centrally. Repair of the ischemic valve is performed by placing a *complete* ring that brings the leaflets together to reestablish the coaptation line, eliminating the regurgitation. Thus, for ischemic disease, rings should be *complete*, and they should be relatively *undersized*. If central leakage exists on passive testing after placing the ring, one may be tempted to place an edge-to-edge stitch. This temptation should be resisted because this will create mitral stenosis in the majority of situations. In ischemia, complete rings are often sized to 24, 26, and 28. These sizes do not ordinarily permit any edge-to-edge repair to be performed without creating a stenotic valve. In this situation, the valve should be replaced.

Mitral valve replacement

Valve excision

A margin of 3–4 mm of native tissue should be left with the annulus so that the prosthesis can later be sutured securely. The posterior leaflet can usually be left intact and incorporated into the valve stitches to preserve the left ventricular-mitral annular continuity that is so important to ventricular

contractility. In most cases, the native subvalvular apparatus can be preserved as this will help maintain normal left ventricular geometry and function. When the subvalvular structures are too calcified and require resection, one should excise just the chordae and not the papillary muscle. Excess tension on the chordae may cause either a hematoma or hole in the ventricular wall, leading to possible wall rupture. Any perforation in the left ventricular wall must be immediately recognized and repaired with pledgeted sutures or Teflon strips.

The calcified annulus

In the situation of extreme calcification of the posterior annulus, one may remove the entire calcium bar in radical fashion, which essentially partially detaches the left atrium from the left ventricle [33]. Our approach is to excise and debride just enough calcium to allow satisfactory stitch placement for either ring annuloplasty or valve replacement. For valve replacement, removal of calcium in the left ventricle is mandatory. For these circumstances, the pledgets must be placed on the ventricular side to minimize torque on the calcified annulus. These can be very difficult stitches to place, and it is common for the pledget to be as far away from the annulus as 1 cm or more. Use of a large MH needle may be required. During debridement, embolism may occur when debris fall into the ventricular cavity. The prevention of this complication is similar to that during aortic valve surgery: a sponge may be placed into the ventricular cavity during debridement to catch debris, followed by copious irrigation.

Annular stitch placement

Like ring annuloplasty stitches, the orientation of the mattress stitches through the annulus should be approximately orthogonal to the annular plane. Sutures should be placed deep into the LV muscle. It is tempting to place stitches into the margin of mitral leaflet tissue left behind during the valve excision. *This should be avoided because these leaflet remnants are not part of the true fibrous skeleton of the heart and do not provide anchoring security.* Stitches should be placed into the annulus itself, using noneverting stitches for bioprosthetic valves and everting stitches for mechanical valves.

Valve seating

Retained native valve tissue, chordal structures, or papillary muscles can interfere with leaflet function in mechanical prostheses. Leaflet mobility should be double checked to ascertain freedom from subvalvular interference. Any tissue touching the leaflets should be excised prior to left atrial closure. Mechanical prosthesis should always be oriented in an antianatomic fashion not only to minimize this possibility, but also to minimize disturbances to the leaflets from left ventricular outflow tract blood flow. When leaflet interference does occur after weaning from bypass, bypass must be reinitiated, the prosthesis removed, and the tissue causing the obstruction excised. The valve

is then reinserted. The use of everting mattress sutures helps prevent this complication, as this technique pushes the annulus of the prosthesis away from the underlying tissue.

Strut location for bioprosthetic valves is extremely important. Struts should be oriented such that they do not come into contact with the ventricular wall or impinge on the left ventricular outflow tract. This may cause significant dysrhythmias or, more importantly, ventricular perforation. This is usually prevented by orienting bileaflet, mechanical valves in the antianatomic fashion. While the use of a nonstrutted prosthesis and preservation of the posterior leaflet and papillary muscles can help prevent this complication, the most important factor is meticulous surgical technique and diligence. Once the bioprosthetic valve is inserted, strut location should be inspected by direct vision using a dental mirror.

Postoperative complications

Thromboembolism is the most common postoperative complication of both bioprosthetic and mechanical valves. Chronic atrial fibrillation and a large left atrial size significantly increase the risk of clot formation [19, 34, 35]. Thrombolytics may be used to treat mitral prosthetic thrombosis as long as the patient is not in cardiogenic shock. If thrombolysis fails, or if there is hemodynamic compromise, valve replacement is required [36–40].

Prosthetic valve degeneration is the most significant complication of bioprosthetic valves. The probability of such structural failure can reach as high as over 60% at 15 years, particularly in younger patients [17, 41–43]. The failure rate in patients 70 years of age or older is substantially less than in younger patients, possibly due to smaller hemodynamic stresses placed on the valve. Valve degeneration can present as either mitral regurgitation from leaflet tear or mitral stenosis from leaflet calcification. Either finding in a postoperative patient requires investigation. The treatment is reoperation to replace the prosthesis.

Paravalvular leak can occur because of poor surgical technique or weakness and tearing of the annular tissue. This is best avoided by using pledgeted mattress sutures in a noneverting fashion and choosing a prosthesis with a substantial sewing ring in patients with weak annular tissue. Reinforcement with a strip of Teflon may be needed. If a paravalvular leak occurs postoperatively, reoperation is required. The leak may be repaired primarily, but often the valve must be replaced with a new prosthesis.

Tricuspid valve

Anatomy

The tricuspid valve is a trileaflet structure that separates the right atrium from the right ventricle. Its three leaflets—the septal, anterior, and posterior—are composed of fibrous endocardium and are in continuity with the valve's fibrous annulus [Figure 18.4]. An important concept in surgery of the tricuspid

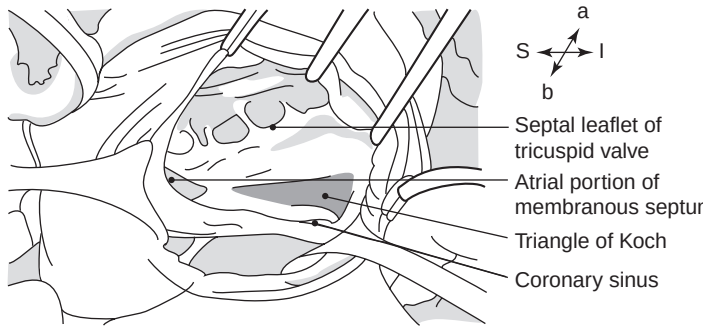

Figure 18.4 The tricuspid valve and structures of surgical importance.

valve is the triangle of Koch, consisting of the septal leaflet of the tricuspid valve, the tendon of Todaro, and the coronary sinus. Within this triangle are the atrioventricular node and the bundle of His. The AV node lies in the atrial septum near the anterior edge of the septal leaflet, and the bundle of His runs from the atrioventricular node under the membranous part of the interventricular septum.

Approach/incision

Tricuspid valve procedures are frequently done in conjunction with another cardiac surgical procedure such as coronary artery bypass grafting or valvular procedures. Hence, the median sternotomy is the most frequent incision. The right atriotomy should be made parallel to the atrioventricular groove, and should not come closer than 1 cm of the superior edge of the right atrium, as this is where the sinoatrial node is located and can potentially be injured. The atriotomy itself should be parallel to the atrioventricular groove but not closer than 1 cm from the groove itself to avoid injury to the right coronary artery that courses in the groove itself.

Annuloplasty

There are two general type of tricuspid annuloplasty: those with prosthetic annuloplasty rings and those that utilize solely suture techniques (e.g., DeVega annuloplasty). Both types are used to repair functional tricuspid insufficiency. The possible complications for both are similar, with the majority related to residual tricuspid insufficiency or arrhythmias. Several studies have shown that freedom from repair failure was similar whether or not a prosthetic ring was placed, while other studies indicate that the suture-only techniques lead to more recurrent tricuspid insufficiency [44–46]. In general, unless there are systemic symptoms or severe manifestations of tricuspid regurgitation preoperatively, our practice is to utilize simple suture bicuspidization for functional regurgitation [46]. In performing suture bicuspidization by obliterating the posterior annulus, care must be taken to avoid kinking the right coronary artery. This is avoided by taking bites only deep enough to penetrate the

annulus without inclusion of an excessive amount of atrioventricular groove tissue.

Rhythm disturbances usually are secondary to injury to the sinoatrial node, the atrioventricular node, or the conduction system fibers. *These complications are best prevented by meticulous surgical technique, judicious suture placement, and a thorough understanding of the anatomy*. The sinoatrial node is located beyond the superior margin of the right atrium. The edge of the atriotomy should be well away from this area, and special care should be taken with respect to this area during cannulation. The atrioventricular node is most often injured by suture placement. Sutures should be located away from the coronary sinus orifice. Sutures should *exclude the septal segment*, avoiding the conduction fibers.

Tricuspid valve replacement

Tricuspid valve replacement can be performed with either a mechanical or bioprosthetic valve. The indications for replacement are lupus, endocarditis, or severe rheumatic disease; in the vast majority of cases; however, repair is usually possible. Several long-term studies have demonstrated no significant benefit of one type of prosthesis versus the other [47–49]. However, most surgeons avoid mechanical valves in the tricuspid position, as these tend to thrombose more frequently and require a higher level of anticoagulation than bioprosthetic valves. Subvalvular tissue should be left intact to preserve right ventricular morphology and function if possible. The anterior and posterior leaflets with their chordal attachments are typically incised, but the septal leaflet should be left behind. Pledgeted sutures are passed through the annulus *except by the septal leaflet, where sutures should be placed only through the leaflet tissue so as to avoid injuring the underlying conduction fibers*. Sizing of the prosthesis must take into account the size of the ventricle as well as the annulus. A large prosthetic valve implanted into a patient with a small right ventricle can lead to septal injury, particularly if the valve has prominent struts. Struts of trileaflet bioprosthetic valves should be oriented to avoid impingement on the right ventricular outflow tract.

Postoperative complications

Postoperative complications of tricuspid valve repair or replacement include rhythm disturbances, residual tricuspid insufficiency, and prosthetic valve dysfunction.

As in tricuspid annuloplasty, tricuspid valve replacement can lead to rhythm disturbances if the conduction tissues are injured. It is imperative that sutures are placed far enough away from the conduction fibers and the atrioventricular node to avoid such injuries. *In the area of the septal leaflet, sutures should be placed at the base of the valve leaflet rather than in the annulus itself*. Complete heart block is the most serious rhythm complication, and has an incidence of up to 5% in the immediate postoperative period and up to 25% at 10 years [50]. Treatment is placement of a permanent pacemaker.

Residual tricuspid insufficiency is most likely to occur in patients with significant pulmonary hypertension or mitral valve disease. Control of these comorbidities is the best strategy to avoid and treat this complication. Prosthetic valve dysfunction occurs as a result of either fibrocalcific degeneration or functional stenosis. The latter is characterized by high transvalvular gradients and elevated right atrial pressure. The best prevention is by implanting a sufficiently large prosthesis at the time of surgery; if this complication is discovered postoperatively, many surgeons will opt not to operate unless the patient displays significant clinical symptoms or deterioration due to the stenosis.

Conclusion

In summary, as the average age and incidence of patients undergoing cardiac valve surgery increases, the necessity of preventing and recognizing potential complications becomes ever more important. With proper patient selection and meticulous surgical technique, many of these complications can be avoided or treated, and safe and effective valvular surgery can be performed.

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CHAPTER 19

Complications of Myocardial Reconstruction

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Background

Ischemic cardiomyopathy (ICM) accounts for 50–75% of heart failure. The prognosis of patients with ICM is related to ventricular volume. The classic postinfarction left ventricular (LV) aneurysm that occurs after occlusion of a coronary artery is less common today with the rapid reestablishment of coronary flow via percutaneous coronary interventions. Infarcts that result in scar should be distinguished from LV aneurysms that are full-thickness attenuated, thin myocardium. The distinction between akinetic and dyskinetic LV aneurysms is related to the extent of infarcted tissue and function of surrounding myocardium.

The pathophysiology of heart failure includes two important related elements: (i) LV contractile dysfunction and (ii) LV dilation and remodeling. It is clear now that ventricular remodeling after infarction results in systolic as well as diastolic dysfunction. The current thinking is that LV chamber dilation occurs as a response to reduced wall motion, which is necessary to generate a normal stroke volume. Consequently, the LV chamber length and shape dilates, or remodels, and leads to an increase in wall tension and further myocardial ischemia. The degree of remodeling correlates directly with poor prognosis and is the key to the severity of reduced ejection fraction [1]. Fortunately, some aspects of the remodeling process are reversible [2]. Structural abnormalities, such as with LV aneurysms that result from an extreme extent of remodeling, alter the efficacy of LV contraction.

LV reconstruction—general concepts

The main goals with LV reconstruction are to improve LV function by (i) excluding the akinetic or dyskinetic segment of LV wall, (ii) decreasing wall

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tension, (iii) improving muscle fiber alignment, and (iv) restoring a more physiologic elliptical LV cavity. Two common approaches include the endoventricula circular patch plasty (surgical ventricular restoration or SVR) and the linear closure technique.

The efficacy of the endoventricular patch technique was evaluated in 1198 patients in the multinational, mulitcenter RESTORE trial; 89% underwent concomitant CABG, and 26% had concomitant mitral repair or replacement [3]. The 30-day mortality was reported to be 5.3% and less than 10% required mechanical support. At 5-year follow-up, LV ejection fraction (EF) improved from 29 ± 11% to 39 ± 12%, and the LV end-systolic volume index decreased from 80 ± 51 to 57 ± 34 mL/m^2. The 5-year freedom from readmission for CHF and survival were 78% and 69%, respectively, and an impressive 85% of patients remained in NYHA class I or II. Improvements in the end-diastolic volume index, EF, and symptomatic heart failure status are maintained 5 years after surgery [4].

We documented SVR does not add significant morbidity to CABG in patients with ICM, with an operative mortality of 3.4% [5, 6]. Furthermore, an analysis of the cost of heart transplantation versus LV remodeling procedures in similar patients at our institution demonstrated the total cost of heart transplantation (including costs of donor procurement) was significantly higher among the heart transplant group [7]. Yet, operative survival was similar between the heart transplant and alternative groups [7].

Although we prefer the SVR technique, linear repair can be performed for smaller akinetic segments of the LV. A recent meta-analysis comparing SVR to linear repair suggested marginally better outcome with SVR [8]. The end result of either technique is an altered shape of the left ventricle. Namely, ventricular reconstruction produces an elliptical shape during systole leading to a more optimal geometry and improved ventricular performance [9].

Anatomy

LV aneurysms occur in the distribution of an occluded coronary artery. The most commonly occluded vessel leading to infarction and ventricular aneurysm formation is the left anterior descending (LAD) artery. Less frequently, the inferior infarction due to posterior descending artery occlusion (via right or left dominant coronary artery systems) results in an inferior wall aneurysm. Since the papillary muscles are contiguous with the ventricular myocardium, LV dilation and remodeling can alter the subvalvar apparatus and lead to mitral regurgitation (MR). Inferior myocardial infarction or aneurysm is associated with posteromedial papillary muscle displacement and tethering of the mitral valve, while anterior infarction or LV aneurysm can be associated with anterolateral papillary muscle displacement. These relationships become important in determining the need for mitral valve surgery in patients with concomitant LV aneurysm and MR.

Table 19.1 Indications for LV reconstruction.

1. Anteroseptal MI, with dilated left ventricle (end-diastolic volume index > 100 mL/m^2)
2. Depressed LV ejection fraction (even under 20%)
3. LV regional dyskinesis or akinesis of greater than 30% of the ventricular perimeter
4. At least one of the following:
(a) Symptoms of heart failure
(b) Arrhythmias
(c) Ischemia on provocative tests in asymptomatic patients

Patient selection

Appropriate selection of patients for ventricular reconstruction is paramount to ensuring good outcomes. Recommendations for indications for ventricular reconstruction are listed in Table 19.1. Optimal patients have symptoms of heart failure or ischemia, and have had an anteroseptal myocardial infarction (MI) with a dilated LV (end-systolic volume index > 60 mL/m^2 or end-diastolic volume index > 100 mL/m^2). Low EF alone does not preclude LV reconstruction as this is a poor predictor of mortality [5]. The size of the scar is more important than whether it is akinetic or dyskinetic. In our experience, the greatest improvement in LVEF occurs when LV regional akinesis/dyskinesis is greater than 30% of the ventricular perimeter.

Recent MI was once considered a contraindication to LV reconstruction. However, Di Donato and others reported an impressive operative mortality of 5.4% in 74 patients undergoing LV reconstruction within 30 days of anterior MI [10]. In this report, only 23% had SVR and the remainder underwent linear closure [10]. Our experience supports this with no mortalities in the subset of patients who underwent SVR with a recent MI [11]. Preoperative ventricular tachycardia (VT) has also been considered an indication for SVR. Sartipy and colleagues reported a series of 53 patients who underwent SVR and surgical VT ablation [12]. Postoperatively, over 85% of patients did not have inducible VT, and no patient had an arrhythmia-related death.

Evaluation of the left ventricle to diagnose and confirm the presence of an LV aneurysm is necessary. Several methods are available including echocardiography, ventriculography, or magnetic resonance imaging (MRI).

Echocardiography allows assessment of the ventricular wall thickness and contractile function of all segments of the LV. Akinetic and dyskinetic segments can be distinguished from contracting segments of the LV. EF can be calculated by measuring endocardial area in systole and diastole in two views. Evaluation of the mitral valve and mechanism of MR is best assessed by echocardiography.

Left ventriculography, once considered the gold standard to evaluate EF, can also identify noncontractile regions. The right anterior oblique view assesses the anterior wall, inferior wall, and apex, while the left anterior oblique view can assess the septal and lateral walls. MR can be seen although the mechanism is difficult to assess.

Cardiac MRI is becoming more commonplace and is useful for identifying ventricular aneurysms, myocardial viability, associated MR, and accurate assessment of EF. MRI with delayed gadolinium enhancement is considered by some to be the most accurate method to predict viability, especially in the setting of revascularization [13]. Furthermore, compared to other modalities, MRI may be the best method to measure LV volume.

Viability testing should be considered in patients who have heart failure symptoms particularly without angina prior to an operation. Regions of viability should be revascularized if appropriate targets are present. A number of viability studies are available and are discussed elsewhere.

Incisions and cardiopulmonary bypass

While other less invasive incisions such as ministernotomy can be used, the complex nature of patients with LV aneurysms and the frequent need for concomitant CABG or mitral valve surgery most often necessitates a full median sternotomy. Standard aortic and venous cannulations are performed. The choice between single and double venous cannulation is dependent upon the need for a concomitant mitral procedure. An LV vent inserted through the right superior pulmonary vein is helpful, but not necessary, for visualization during LV reconstruction. The presence of intraventricular thrombus by intraoperative transesophageal echocardiography (TEE) precludes insertion of an LV vent. After institution of cardiopulmonary bypass, mild systemic hypothermia (32–34°C) is used. Antegrade with or without retrograde cold blood cardioplegia is administered. An initial dose of warm blood cardioplegia should be considered for patients with acute or ongoing ischemia. After completion of coronary bypass grafting and mitral valve procedures, the LV reconstruction procedure is performed. The classic SVR procedure, popularized by Dor, was performed in an area of a large anterior wall infarct on a beating heart without the cross-clamp. As discussed below, it is our preference, however, to perform this procedure with the heart arrested.

Concomitant CABG

Targets for coronary revascularization should be determined preoperatively by cardiac catheterization and viability studies. Revascularization is typically performed first so that cardioplegia can be administered into the grafts to ensure optimal myocardial protection during the remainder of the operation. The choice of conduit is made based on various risk factors including age, presence of comorbidities such as chronic obstructive pulmonary disease and body mass index, and availability and adequacy of conduit. Our preference is to use a left internal mammary artery conduit to anterior wall targets when possible. In cases of anterior wall aneurysm, the need to revascularize the LAD artery is determined by the presence of viable myocardium in its

territory. In these cases, this anastomosis is typically performed before the LV reconstruction procedure.

Concomitant mitral valve procedure

The determination of the requirement for mitral valve repair in the setting of SVR has been a point of controversy. Reduction of the LV size alone improves MR to some extent. A recent study by Di Donato and colleagues evaluated postoperative MR in 55 patients who underwent anterior SVR with mild MR preoperatively. Without mitral repair, ischemic MR improved in 70% of patients, while MR did not improve or was worse in 29% [14]. In this series, patients with improved MR had significantly smaller end-systolic and end-diastolic volumes after SVR compared to those patients in whom the MR did not improve [14]. The improved MR may further be related to shortening of the papillary muscle distance. Our group also noted an improvement in MR in 60% of patients with mild to moderate MR in patients who went SVR alone [15]. Our current practice is to repair the mitral valve in cases of severe MR. Patients with mild to moderate MR are likely to improve with LV reconstruction alone. Mitral repair should be considered in patients with moderate to severe MR with a significantly dilated annulus ($\geq$40 mm).

We prefer to address the mitral valve through a standard left atrial approach. Since the mechanism is usually ischemic in nature, a semirigid ring downsized by two sizes allows improved coaptation of the leaflets. As discussed in detail in the chapter on mitral valve surgery, care must be taken to avoid damage to the circumflex artery in these patients with ICM. After completion of the coronary artery bypass grafting and mitral valve repair, attention is turned to the LV reconstruction.

Ventriculotomy

The presence of an LV aneurysm is confirmed intraoperatively. While on cardiopulmonary bypass, the thin LV aneurysm often dimples. Visualization of the aneurysm can be enhanced with negative pressure placed on the LV vent. Our preference to perform ventricular reconstruction with the heart arrested is supported by our experience that ventricular reconstruction with the beating heart provides no additional advantage [11].

The longitudinal ventriculotomy is performed parallel to the course of the coronary arteries. In the case of an anterior LV aneurysm, this should be performed at a minimum of 2–3 cm lateral to the LAD artery to allow safe closure of the ventriculotomy. An incision closer to the LAD will risk injuring this vessel with the epicardial closure of the aneurysm, and is particularly important when grafting this vessel. The aneurysm is opened beginning at the apex and moving superiorly to completely visualize the extent of the aneurysm that is thin walled but may be trabeculated or smooth. Stay sutures are used to maintain exposure of the endocardial surface of the ventricle. Intraventricular clot often present in the trabeculated muscle must be

visualized and carefully removed. When present, we avoid aggressive irrigation of the LV to minimize risk of clot embolization. The subvalvar apparatus of the mitral valve is easily visualized.

Defining neck of aneurysm

Defining the transition between scarred tissue and viable tissue is critical. Proponents of the beating heart method believe digital palpation of the ventricle allows the surgeon to discriminate between noncontracting muscle and healthy muscle along the border zone [16]. This fine distinction using digital exam is difficult and makes suture placement more complex. Furthermore, placement of the exclusion stitch is much harder in a beating heart particularly with a recent infarct. With the heart arrested, the transition between normal myocardium and dysfunctional scar is often well visualized: The scarred LV aneurysm is typically gray-white while the viable myocardium is fleshy red. Often the aneurysm extends close to the base of the papillary muscles and includes the septal wall. Other benefits of performing myocardial reconstruction with the heart arrested include the ease of suture placement and a minimized risk for air embolism. Both of these reasons make the beating heart method more challenging.

Furthermore, despite the argument that the beating heart method may be preferable in the setting of acute MI, we still prefer to reconstruct the ventricle with the heart arrested as the distinction between healthy and necrotic, friable tissue is usually still apparent.

Sizing the ventricle

Prediction of the ventricular size is often the area of greatest concern. A number of tools and formulas are available to determine the optimal size of the ventricle given a patient's size, body surface area, and body mass index. Some authors use an elliptical balloon inflated to a volume of 50–75 mL/m^2 of body surface area to determine the optimal predicted size of the LV. Our approach has utilized a multidisciplinary approach to address the predicted LV volume. LV internal dimensions at end-systole and end-diastole are obtained primarily from parasternal long-axis echocardiographic views. Akinetic and hypokinetic segments are easily identified and the degree of ventricular reduction required is obtained from these views. We believe the location of the Fontan stitch and subsequent ventricular volume can accurately be determined preoperatively with echocardiography and the use of ventriculograms. Once the base of the LV aneurysm and size is determined, the 2-0 prolene purse-string stitch is placed around the circumference of the scar at the transition zone that is usually at the base of the papillary muscles. As this suture is tied down, the size of the new ventricular opening is determined.

Overaggressive reduction of the LV should also be avoided. Overcorrection of the LV size can limit diastolic filling due to a lack of diastolic elastance, thereby creating a restrictive pathology of the ventricle. Thus, an LV with

systolic dysfunction will be compounded by diastolic dysfunction. LV reduction, when kept to less than one-third the preoperative ventricular volume, will usually avoid this dreaded complication.

Closure of the ventricle

The future shape of the ventricle should be considered when performing the Fontan stitch as this stitch will define the extent and orientation of the endocardial patch. It is preferable to place the patch in an oblique orientation to the plane of the mitral valve, resulting in an elliptical shape of the LV. If the patch is placed parallel to the mitral valve, the shape of the LV will remain spherical and the optimal performance of the LV may not be achieved.

A synthetic (Dacron) or pericardial patch is measured and secured to the ventricular opening with running 3-0 prolene suture (Figure 19.1). The patch

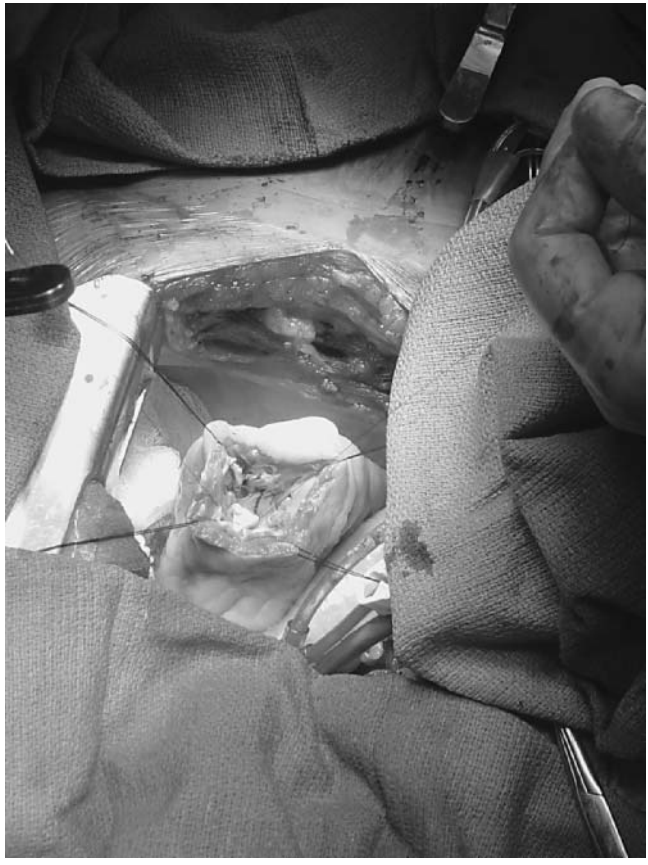

Figure 19.1 Endoventricular patch being sutured to exclude the neck of an anterior wall LV aneurysm.

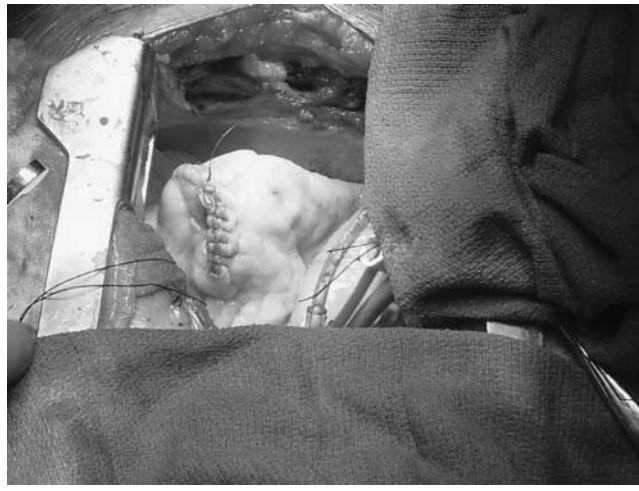

Figure 19.2 Completion of the LV reconstruction, with double-layer closure of the myocardium.

should be fashioned such that it is not redundant to optimize exclusion of noncontractile segments. This single-layer patch is often not hemostatic, which is acceptable due to the fact that closure of the epicardial layer will ensure hemostasis. The second-layer closure of the ventricular aneurysm is performed by reapproximating the free edges of the ventricular free wall. This closure is performed with a running horizontal mattress layer following by a running over-and-over stitch with 3-0 prolene (Figure 19.2). In cases of a recent MI, closure of the ventricle can be performed with the use of longitudinal felt strips as the myocardial tissue is more friable than chronic scar.

Inferior ventricular reconstruction

Aneurysmal dilatation of the inferior wall is due to infarction of the posterior descending or circumflex arteries. With the heart arrested, a longitudinal ventriculotomy is made. The ventriculotomy must end short of the mitral annulus, and the incision is carried medial to the papillary muscle to avoid injuring the subvalvar apparatus of the mitral valve. As these aneurysms are often smaller than those related to anterior infarcts, inferior reconstruction is often performed with linear closure. Large posterior infarcts that involve the papillary muscle may require mitral valve replacement, which can be performed through the ventriculotomy. Closure of the ventriculotomy in cases of large posterior infarctions is best performed using a triangular-shaped patch. As described by Dor, the widest portion of the patch is secured to the base of the LV, near the mitral annulus [17].

De-airing and arrythmias

After closure of the ventriculotomy and completion of the proximal anastomoses of the bypass grafts, we administer "hot shot" warm cardioplegia. As with other open procedures, carbon dioxide is continuously irrigated onto the surgical field. De-airing of the LV is performed by allowing the heart to fill and insufflating the lungs, while maintaining suction on the aortic root vent. The cross-clamp is removed with the patient kept in Trendelenburg position. The root vent is kept on until complete de-airing is confirmed by TEE. In addition to altering the position of the heart, Valsalva maneuvers can prove useful in de-airing. Air in venous bypass grafts can be removed with stab incisions made with a small needle (27G). Initial cardioversion for ventricular arrhythmias is best performed on an empty heart to avoid LV distension. If cardioversion is unsuccessful, often allowing the heart to fill prior to repeat cardioversion ensures better conduction of the electrical impulse and successful cardioversion. Persistent ventricular arrhythmias should suggest areas of ischemia due to air in the coronary vessels, a kinked bypass graft, or ungrafted areas of ischemia. In patients with drug eluting stents, ventricular arrhythmias may suggest occlusion of the native coronary vessel if clopidogrel is stopped perioperatively [18].

Postoperative ventricular arrhythmias

Despite excluding scar on the left ventricle during reconstructive procedures, it is not uncommon for patients to develop ventricular arrhythmias postoperatively. O'Neill and associates from the Cleveland Clinic demonstrated that 42% of patients who underwent SVR have inducible VT during provocative electrophysiology (EP) study [19]. This has led some to believe all patients should undergo provocative EP testing prior to discharge after SVR [19]. Critiques of this study argue that the majority of patients in this series underwent linear closure (83%), and very few underwent ablation for preoperative VT. These findings are in contrast to other large series that indicate up to 90% of patients are free from inducible VT with the endoventricular patch technique [20]. The discrepancy between these two studies may lie in differences in reduction in the LV volume and wall tension with the two techniques. Nevertheless, insertion of an implantable cardioverter defibrillator should be considered in any patient with preoperative or postoperative VT. In patients with preoperative VT, consideration should be given to intraoperative mapping and surgical ablation of the VT at the time of LV restoration.

Separation from bypass

As this procedure is performed on patients with low EF and with ICM, separation from bypass may be complicated. The RESTORE trial suggested that most patients with complete revascularization and improved LV contraction

after reconstruction are able to separate from the bypass circuit with the use of mild to moderate doses of inotropes and vasopressors. Furthermore, an intra-aortic balloon pump (IABP) was needed in 8% of patients, while perioperative insertion of a LV assist device (LVAD) was needed in less than 1% of patients [3]. Our experience supports these findings as 13% required the use of an IABP and no patients were subjected to LVAD insertion perioperatively [11]. The use of intraoperative TEE can distinguish causes of LV dysfunction or failure while attempting to wean off bypass.

Embolization

Left-sided embolization can occur from air or debris within the LV. Thus, careful removal of clot and complete de-airing during LV reconstruction is necessary. Embolization can occur to any end organ and lead to stroke, intestinal ischemia, renal insufficiency, or lower extremity ischemia. A high index of suspicion is needed to diagnose these catastrophes. We discovered a clot originating from the LV that embolized to the left main coronary artery and resulted in severe LV dysfunction while weaning off bypass [21]. This was visualized by TEE and removed via aortotomy [21].

Bleeding

Bleeding from the ventriculotomy site is uncommon using the double-layer closure technique as described above. Minor bleeding from needle holes will usually cease after heparin reversal. More significant bleeding will require additional reinforcing sutures. In the setting of recent MI, bleeding from the ventriculotomy requires the use of pledgeted sutures to avoid tearing through the friable myocardium. More extensive bleeding should prompt TEE to ensure that the endoventricular patch is well seated.

Future

The ongoing Surgical Treatment for Ischemic Heart Failure (STICH) Trial, a randomized, prospective study to determine the optimal treatment for patients with coronary artery disease and EF $< 35\%$, will answer several questions [22]. Patients who are candidates for LV reconstruction and CABG will be randomized to best medical therapy, CABG alone, or CABG plus SVR [22]. In addition to determining the optimal treatment for these patients, long-term outcome and durability of SVR results will be determined.

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CHAPTER 20

Complications after Atrial Fibrillation Surgery

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The Cox-Maze (CM) procedure was introduced in 1987 by Dr. James Cox for the surgical treatment of atrial fibrillation (AF). After several modifications, the CM III emerged as the gold standard for the surgical treatment of AF. The CM III involves creating lines of conduction block by making incisions in both atria. These lines of block are designed to interrupt the macroreentrant circuits thought to be responsible for AF [1, 2]. In long-term follow-up, the CM III has achieved an over 90% success rate in curing symptomatic AF [3]. Unfortunately, the CM III was not widely adopted because it was time-consuming and technically demanding. Thus, many groups have replaced the incisions of the CM III with lines of ablation using various energy sources [4–9]. A number of new operations have been introduced using this new ablation technology. These have included pulmonary vein isolation, a wide range of left atrial lesion sets, and the full CM lesion set performed with ablation devices (Figure 20.1).

The safe use of these new ablation devices requires a thorough understanding of their dose-response curves and the biology of the lesion formation. Most unipolar devices radiate heat or cold from a point source. These include unipolar radiofrequency (RF), cryothermy, microwave, and laser energy. These devices each have unique dose-response curves that vary depending on the physiological milieu. Critically, lesion depth can vary depending on whether ablation is performed in the arrested or beating heart. Intramyocardial perfusion, tissue temperature, and endocavitary blood flow have all been shown to have an effect on lesion depth and width [10–17]. A thorough understanding of lesion formation is necessary to avoid collateral injury to cardiac and extra-cardiac structures.

Bipolar RF is a focused energy that can avoid some of these problems [18]. Bipolar RF focuses the energy between the jaws of a clamp without significant thermal spread outside the clamped tissue. This makes collateral injury to other structures unlikely unless the structure itself is clamped. The

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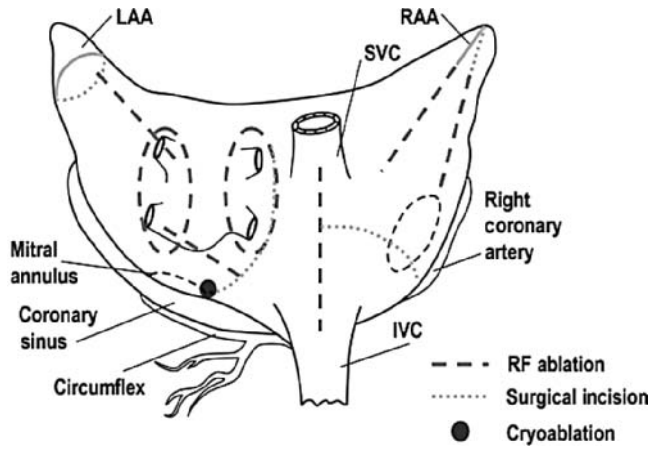

Figure 20.1 The modified Cox-Maze IV. The majority of lines of conduction block are created with bipolar radiofrequency energy. (*Source*: From Ref. [41].)

disadvantage of bipolar RF is that it requires tissue to be clamped between the jaws of a device, which limits the types of ablations that can be performed. These devices have particular difficulty creating lesions around the valve annuli.

Short-term results with many of these new techniques and technologies have been good, and the number of operations for AF has risen steadily over the last decade [4, 9]. The following chapter describes common complications after AF surgery.

Intraoperative complications

Atrial-esophageal fistula

As different technologies are used to replace the incisions of the CM procedure with lines of ablation, new complications have arisen. One of the most morbid complications has been the creation of atrial-esophageal fistulas and esophageal perforation. This problem is created by the endocardial application of unipolar thermal energy along the posterior left atrium where the left atrium and the esophagus are closely approximated [5].

Common symptoms of atrial-esophageal fistula include hemoptysis, hematemesis, and gastrointestinal hemorrhage as a direct result of bleeding through the fistula. Patients may also present with fevers as a result of an infection seeding from the esophagus directly into the bloodstream. The presentation of esophageal fistula can be dramatic and delayed. In one series that reported four cases of fistula, three patients had initially unremarkable postoperative courses until they developed sudden symptoms from air embolism, including transient ischemia attacks and angina pectoris. These symptoms developed 10 ± 3 days postoperatively. The last patient presented with gastrointestinal hemorrhage [19].

When an esophageal injury is suspected, it is imperative that evaluation be done with caution. Two separate groups have reported deaths from aorto-esophageal fistula as a result of massive cerebral vascular accident caused by embolization of insufflated air during esophagoscopy [19, 20]. A CT-scan with water-soluble contrast should be used to make the diagnosis.

Of note, this injury may be device specific. The only reports of esophageal injury have been with unipolar RF energy [7, 20, 21]. There have been no reports of esophageal injury with bipolar RF, cryosurgery, or other unipolar energy sources.

To avoid esophageal injury, special care should be taken to shield the esophagus from thermal damage when performing endocardial ablation on the posterior left atrium with a unipolar energy source [19]. A dry surgical sponge can be placed in the pericardial space to shield the esophagus from RF ablation [5]. Also, ablation can be performed from the epicardial surface toward the endocardium to direct the thermal energy away from the esophagus.

Coronary artery injuries

With the original CM III procedure, it was recognized that coronary artery injury was possible, especially to the circumflex coronary when performing the left atrial incisions [2]. None of the energy sources presently used for the surgical ablation of AF have been shown to be safe on coronary arteries. A few studies have looked at 30-day histology, but this is inadequate since it does not rule out late intimal hyperplasia [22]. In a study looking at chronic histology in an atherogenic model, cryoablation was shown to result in late intimal hyperplasia [23]. Heat-based ablation would be expected to cause more acute injury based on its ability to denature protein and coagulate blood. Thus, as unipolar energy sources were increasingly applied to replace surgical incisions, there have been reports of injury to the coronary arteries. One case report described a patient suffering a myocardial infarction due to a lesion in the left main coronary artery from microwave ablation [24]. Similarly, in a series using unidirectional RF energy, a patient developed angina 6 weeks after ablation and required percutaneous stent placement [5]. The presentation of this complication can be quite delayed. One report in the literature details the presentation of a patient 12 months after her unipolar RF ablation procedure with stenosis developing in the circumflex artery along the line of ablation on the left atrium [25].

Special caution should be exercised in proximity to the coronary artery at all times, regardless of the energy source. Coronary artery injury can also occur following amputation of the left atrial appendage. One group has reported creation of a coronary artery fistula at the site of left atrial appendage amputation [26]. Fortunately, the fistula resolved without intervention on follow-up evaluation. In order to avoid injury to the circumflex coronary artery, surgeons should be careful not to place sutures or the staple line too close to the atrioventricular groove, as the circumflex artery runs in this area.

Left atrial appendage injury

An important component of surgery for AF is the removal of the left atrial appendage. In the traditional cut-and-sew CM III procedure, this was done by surgically excising the appendage and then oversewing the stump with suture. In the two decades in which the CM procedure has been performed, there has been only one reported injury related to amputation of the left atrial appendage [26]. With the advent of surgical ablation devices, and in particular beating-heart approaches to AF without cardiopulmonary bypass, surgeons have begun looking at alternate methods of removing the atrial appendage. Stapling the appendage has become popular in some centers.

This has led to a number of complications. One study reported tears in both the left atrium and the left atrial appendage during manipulation of a stapler device when trying to occlude the left atrial appendage [27]. However, most of these complications have not been reported in the literature. There have been several cases of severe bleeding due to tears in the left atrial appendage from a stapler misfiring, at least one of which has resulted in mortality.

If a stapler device is used, surgeons should be extremely cautious. If the device is twisted during firing, it can result in a tear of the appendage. The stapler should be held as parallel as possible to the base of the appendage and steadied during staple deployment. Surgeons should be prepared and have a plan to handle bleeding should it occur.

In order to avoid these complications, devices are being developed to occlude the appendage without the use of staplers or the need to amputate the distal appendage [28, 29] (Figure 20.2). This may help avoid these injuries in the future.

Figure 20.2 Example of a device in development by AtriCure, Inc. applied to the canine left atrial appendage designed to occlude the structure.

Postoperative complications

Fluid retention

It has long been recognized that fluid retention is a complication following AF surgery. Most of the morbidity from fluid retention comes from pulmonary complications as a result of pleural effusions. The cause of fluid retention is multifactorial, and is partly related to an alteration in the hormonal milieu after the operation.

Some groups believe that amputation of the atrial appendages leads to abnormalities in atrial natriuretic peptide (ANP) secretion. Animal data have shown a clear link between the atrial appendages and ANP. In a primate model of bilateral atrial appendectomy, ANP secretion was attenuated in response to volume expansion, and subsequent renal urine production was diminished [30]. Furthermore, supplementation of ANP in a rat model of bilateral atrial appendectomy restored normal urine output response to volume challenges [31].

Abnormal ANP secretion after atrial appendectomy has been documented in humans as well [32]. Yoshihara and colleagues documented significantly depressed levels of ANP in patients undergoing the CM procedure in the acute postoperative period (Figure 20.3) [33]. One of the investigators from this group modified the CM procedure to preserve the atrial appendages. In comparison to patients undergoing the traditional CM procedure, these patients had greater secretory reserve for ANP in response to exercise [34].

ANP is not the only alteration in the hormonal milieu of postoperative AF patients. In one study, even though ANP levels were relatively normal, antidiuretic hormone and aldosterone levels were markedly elevated after the CM procedure [35]. Both antidiuretic hormone and aldosterone levels were shown to be elevated two to three times more than a control cohort of coronary artery bypass grafting patients (Figure 20.4) [36]. Following the introduction of ablation devices, fluid retention has become less of a problem in most centers. This may be due to less atrial injury. Moreover, most surgeons now preserve

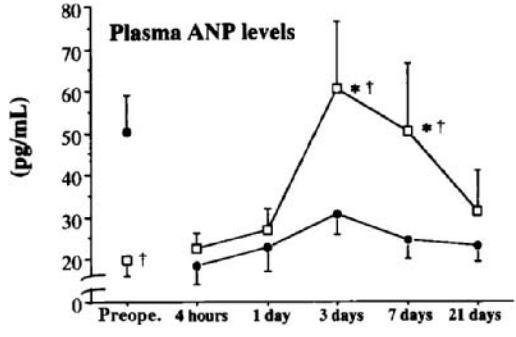

Figure 20.3 Plasma ANP levels after Maze (closed circle) and non-Maze (open square) patients postoperatively. (*Source*: From Ref. [33].)

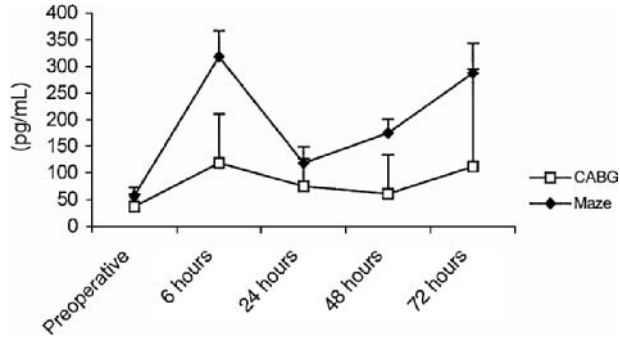

Figure 20.4 Perioperative aldosterone levels in postoperative patients. (*Source*: From Ref. [36].)

the right atrial appendage which also may have decreased the incidence of this complication [8].

Clinical management of these patients has been straightforward. Diuretics should be used liberally in the early postoperative period. Ad and colleagues showed that a continuous infusion of furosemide in the early postoperative period was superior to bolus furosemide. Total dose of furosemide was lower, total urine output was greater, and pulmonary complications were fewer in the group receiving continuous furosemide [37]. Since clinical studies have shown inappropriate antidiuretic hormone (ADH) and aldosterone secretion, spironolactone is an important part of postoperative diuretic management. Spironolactone is administered to most patients for 2–4 weeks to ensure adequate fluid mobilization.

Early atrial arrhythmias

A significant problem in the management of postoperative AF surgery patients is the development of atrial tachyarrhythmias (ATAs) within the first 2 months following surgery. Local atrial inflammation is believed to be the cause of arrhythmias in the postoperative cardiac surgery population. Animal studies have demonstrated that increased inflammation in the heart is associated with an increase in inhomogeneity of conduction throughout the atria [38]. This likely predisposes to AF. Human studies have demonstrated that elevated inflammatory markers, such as C-reactive protein, are associated with the occurrence of arrhythmias after cardiopulmonary bypass [39]. It is not surprising that postoperative AF surgery patients, who undergo extensive manipulation and injury to atrial tissue, suffer from a high incidence of postoperative arrhythmias.

The largest report on postoperative ATAs was published by Ishii and colleagues from Washington University [40]. In 200 patients undergoing the CM procedure, 43% had early ATAs. The majority of these arrhythmias were AF, but there were also episodes of atrial flutter, atrial tachycardia, and supraventricular tachyarrhythmia (Figure 20.5). The majority of these ATAs occurred

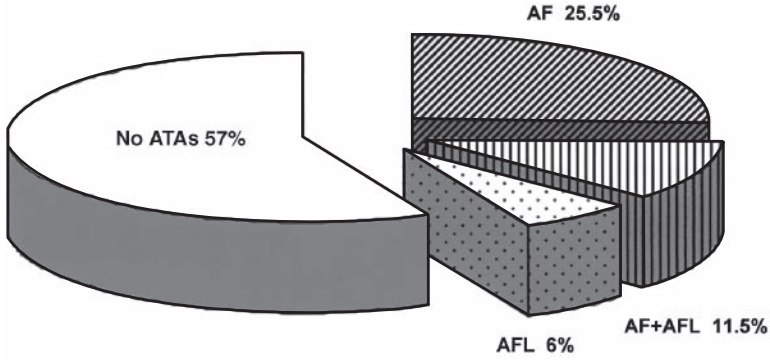

Figure 20.5 Incidence of early atrial tachyarrhythmias (ATAs) after the Maze procedure. AF, atrial fibrillation; AFL, atrial flutter. (*Source*: From Ref. [40] with permission from the American Heart Association.)

within the first 8 postoperative days, and most resolved within 3 weeks (Figure 20.6). The only significant risk factor for the development of arrhythmias in multivariate analysis was increasing age. However, longer duration of preoperative AF, performance of concomitant cardiac procedures, and longer cardiopulmonary bypass time all trended toward significance in predicting which patients developed ATAs (Table 20.1). An important finding of this study was that the presence of ATAs had no impact on the late success of

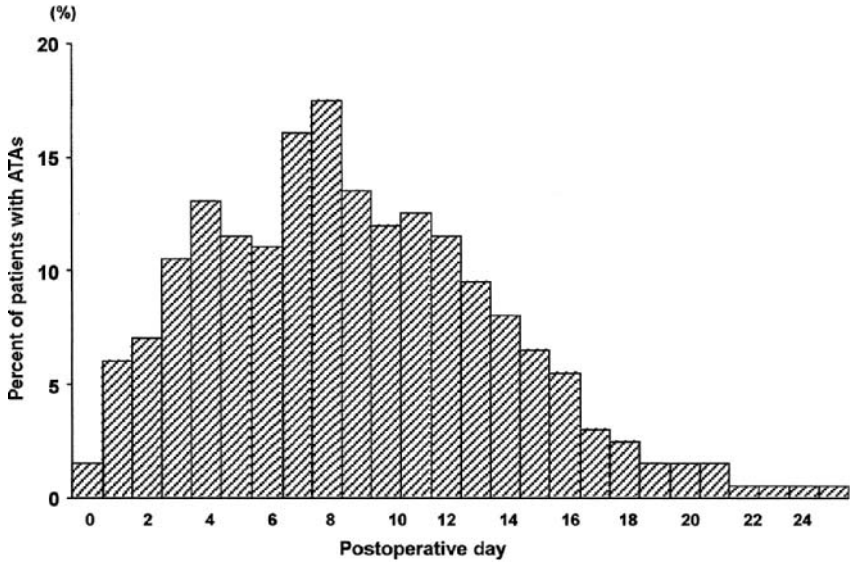

Figure 20.6 Frequency distribution of incidence of ATAs after the Maze procedure. (*Source*: From Ref. [40] with permission from the American Heart Association.)

Table 20.1 Univariate and multivariate predictors analysis of early postoperative atrial tachyarrhythmia.

	Univariate analysis	*Multivariate analysis*
Age	0.003	0.03
Type of preoperative AF	0.3	0.7
Duration of postoperative AF	0.08	0.2
Maze procedure version (I–III)	0.2	0.5
Concomitant procedures	0.06	0.8
Cross-clamp time	0.64	0.17
Cardiopulmonary bypass time	0.04	0.06

p-values from univariate and multivariate analysis of risk factors for early postoperative atrial tachyarrhythmias [40].

the CM procedure. There was no significant difference in late recurrence of AF in patients with or without early ATAs (7% vs. 8%, $p = 0.8$).

There have been no studies evaluating preventive drug regimens in this patient population. In our center, prophylactic antiarrhythmic drugs are used in patients, when tolerated, for the first 2 months. They are discontinued when the patient has resumed normal sinus rhythm.

The treatment for early ATAs should follow standard guidelines for postoperative AF. At our center, our drug of choice is amiodarone intravenously or orally. Other drugs may be used if amiodarone is not tolerated. If antiarrhythmic drugs are not tolerated, anticoagulation alone is appropriate. Cardioversion is usually delayed until just prior to discharge, or at 4 weeks after discharge. Early cardioversion, within the first postoperative week, has been prone to recurrence rates of up to 50% in our experience, likely due to the persistent atrial inflammation. If cardioversion can be delayed for 1 month, success rates have been over 95%.

Sinus node dysfunction and chronotropic incompetence

Patients after surgery for AF may require permanent pacemaker implantation, often due to impaired sinus node function. In the early iterations of the CM procedure, the rate of postoperative permanent pacemaker insertion was as high as 56% [1]. This complication was significantly decreased with the introduction of the CM III procedure, and the rate of permanent pacemaker insertion was 15% in our long-term experience at Washington University [3]. The need for postoperative pacemakers can be a complication of the disease as much as it is a complication of the operative procedure. In the Washington University CM III experience, 78% of patients receiving a permanent pacemaker carried a preoperative diagnosis of sick sinus syndrome [41]. Moreover, the incidence of pacemaker implantation was higher in patients undergoing concomitant valve surgery compared to patients undergoing a lone CM III procedure (23% vs. 8%, $p < 0.05$) [3]. The overall incidence of pacemaker implantation has dropped to under 10% in our recent experience with the

ablation-assisted CM IV procedure [42]. This may be due to less atrial trauma when compared to the traditional cut-and-sew approach. A meta-analysis of over 3800 patients undergoing AF surgery by Khargi in 2005 revealed that 5–6% of patients undergoing AF surgery required permanent pacemaker insertion [43].

Sinus node function can be adversely affected by AF surgical procedures, even in patients without sick sinus syndrome. Patients may develop inappropriate sinus bradycardia at rest, or they may lose the ability to mount an appropriate sinus tachycardia in response to exercise, a condition termed chronotropic incompetence [1]. These patients often clinically present with exercise intolerance, and the diagnosis should be suspected in patients complaining of easy fatigability following surgery. The diagnosis is confirmed by examining the heart rate response during a treadmill test.

The treatment for bradycardia or chronotropic incompetence consists of permanent pacing; however, the decision to implant a permanent pacemaker should be carefully considered. It is difficult to assess sinus node competence in the early postoperative period, and many patients recover normal sinus node function over time. In one series that excluded patients with preoperative sick sinus syndrome, sinus node dysfunction in CM patients was initially similar to that seen in denervated heart transplant patients [44]. On long-term follow-up with Holter monitoring, this resolved in half of the patients at 6 months and in all patients by 12 months. Furthermore, these patients regained the ability to mount a sinus tachycardia in response to treadmill exercise at 12 months [45]. In another electrophysiologic study of a series of 37 patients, no patient demonstrated permanent sinus node damage at a mean follow-up of 45 months [46]. Similarly, in our experience, the majority of patients with postoperative junctional rhythm resolve over the first 6 months. Therefore, the decision to implant a permanent pacemaker should be made with special consideration of the time since surgery, the patient's medications, and the severity of their symptoms. If the patient is tolerating his or her rhythm, the decision to implant a permanent pacemaker should be delayed as long as possible.

Atrial mechanical dysfunction

The CM procedure was designed to restore sinus rhythm and to allow for return of atrial contractile function. Many studies have documented the return of atrial contraction following the CM procedure by echocardiography. In a series from the Cleveland Clinic, 71% of patients had evidence of left atrial function in long-term follow-up by echocardiography [47]. However, atrial function in these patients was worse than normal controls. In a report from Washington University, at late follow-up, 83% of patients had normal right atrial function and 61% had normal left atrial contraction by examining for the presence of an A-wave on echocardiography [48].

In patients with paroxysmal AF and normal preoperative atrial transport function, postoperative atrial transport function may be worse [49]. The adverse impact of the CM lesion set is borne out by experimental studies.

Cardiac magnetic resonance imaging (MRI) in pigs undergoing a CM procedure performed with bipolar RF ablation demonstrated that atrial ejection fraction was decreased using each animal as its own control [50]. In another study, Melby and colleagues demonstrated that postoperative atrial ejection fraction was roughly half that of a group of healthy control animals [22]. While the load-dependent function of the left atrium has been shown to be impaired (i.e., atrial ejection fraction and regional wall shortening), interestingly, load-independent parameters, such as elastance of the atria, were not affected by the full CM lesion set in a recent study [51].

Although there is evidence that atrial function is depressed after the CM operation, the significance of this decreased function is not known. The stasis of intracavitary blood in the fibrillating atrium has been thought to be responsible for embolic events in patients with AF. The abnormally functioning atrium in the postoperative AF surgery patient generally has not predisposed patients to thromboembolism. In the entire experience with the CM III procedure at Washington University, there was only one late stroke in 198 consecutive patients followed for a mean of 5.5 years [3]. This is likely due to the fact that our group and others have shown that approximately 80% of atrial emptying is passive and related most closely to left ventricular compliance [51–53].

The clinical significance of incremental gains in atrial transport function is also uncertain. The radial incision approach to the CM procedure as developed by Nitta and colleagues was designed to improve atrial transport function [54]. A follow-up study examining the effect on atrial transport in patients showed almost a twofold higher atrial ejection fraction as evaluated by echocardiography. The clinical outcome for these patients, however, was not different. The incidence of stroke was 0% for both radial and traditional CM procedures over a follow-up period of up to 22 months [55].

There has been echocardiographic evidence that, following a CM procedure, atria preserve their ability to respond to increased workload. Muraki and colleagues examined 13 patients and showed increases in surrogates of left atrial contraction in response to dobutamine infusion [56]. Furthermore, there has been evidence that atrial function does not worsen over time and may even improve over prolonged follow-up [6, 57].

In light of the high rate of early ATA after operation, systemic anticoagulation for the first 2 or 3 months after surgery is warranted. At our center, anticoagulation is stopped once the patient is documented to have no episodes of AF on prolonged monitoring after discontinuation of all antiarrhythmic drugs. Echocardiography is also performed in all patients prior to discontinuation of Coumadin to rule out left atrial stasis or left atrial thrombus.

Late recurrent atrial fibrillation

While cure rates have been good in many centers following AF surgery, there is a subset of patients that experience late recurrence of their AF. Predictors of late failure include large left atrial size, increased age, and longer duration of preoperative AF [41, 58].

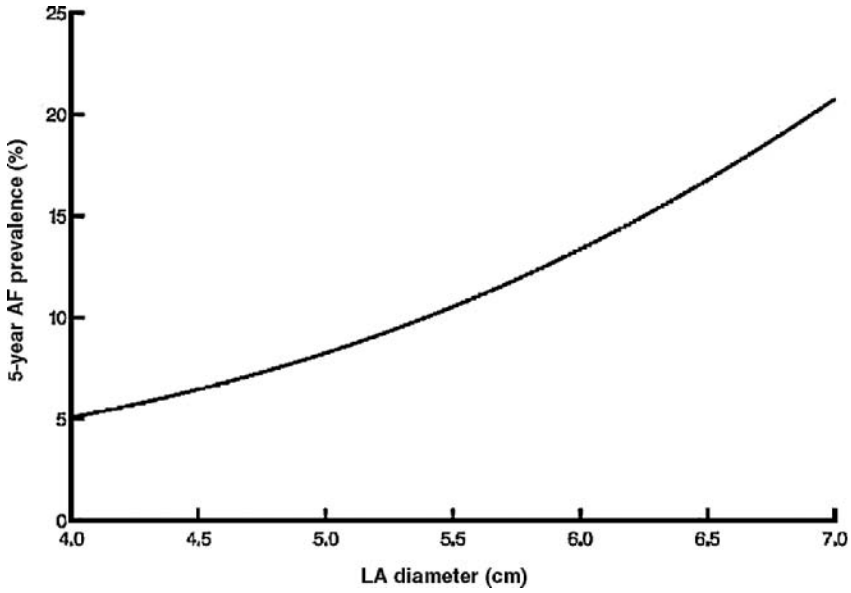

Figure 20.7 The effect of left atrial size on the prevalence of atrial fibrillation after operation. (*Source*: From Ref. [58].)

Several centers have reported failure of the CM procedure in patients with large left atria [58, 59]. In one series out of Japan, all patients with atria larger than 8.7 cm had recurrent AF [59]. In the Cleveland Clinic experience, multivariate analysis revealed that left atrial diameter was an independent predictor of late failure of the CM procedure (Figure 20.7) [58].

As a result of this observation, some groups have modified the CM procedure to include strategies to reduce atrial size. Romano and colleagues achieved an 89% success rate in patients with mean left atrial size of 6.6 cm in diameter treated by aggressively resecting redundant atrial tissue [60]. In another series, there was an increased recovery of left atrial transport function in surgically reduced atria compared to a standard historical group of patients [61]. Short-term results are encouraging, but long-term follow-up has been unavailable, and there have been no randomized trials. Thus, the technique of resection and the amount of atrium needed to be removed remains poorly defined. At our center, the policy is to perform atrial reduction in patients with a left atrial diameter greater than 7 cm. Our technique involves removing a strip of posterior left atrium between the left and right inferior pulmonary veins and the AV groove.

A longer duration of preoperative AF also predicts long-term failure of AF surgical procedures [41, 58]. In our series, patients with 5 years of preoperative AF had a 91% freedom from recurrence at 10 years, while those with 20 years of preoperative AF only had 72% freedom [41].

Since a longer duration of preoperative AF increases the likelihood of treatment failure, appropriate patients with symptomatic AF should be referred to surgery without a long delay. A recent consensus statement from the Heart Rhythm Society, encompassing expertise from the European Heart Rhythm Association, the American College of Cardiology, the Society of Thoracic Surgeons, and other national and international groups has defined the indications for the surgical treatment of AF [62]. It is imperative that cardiac surgeons work closely with referring cardiologists and electrophysiologists to ensure that patients with refractory AF are referred to surgery when indicated.

In summary, there are distinct complications after surgery for AF. Appropriate management will ensure the best outcomes for this increasing population of patients.

Acknowledgments

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CHAPTER 21

Heart Transplantation

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Introduction

Over the past 40 years, cardiac transplantation has become the definitive treatment for end-stage congestive heart failure [1]. Short-term survival has improved secondary to advances in donor and recipient management, operative technique, immunosuppression, and infection prophylaxis. Despite these advances, long-term survival has not changed dramatically during the last 10 years, largely due to chronic rejection, side effects of immunosuppression, and infections [1, 2]. Over the last 3 years, the number of heart transplants performed has remained stable, primarily due to a shortage of donor organs. It is estimated that 25 000 patients annually could benefit from cardiac transplantation [3], yet only 3000 transplants are performed worldwide each year [1]. To overcome this shortage, recent attempts have been made to expand the donor pool, optimize medical management, and provide nontransplant surgical options for heart failure (coronary revascularization, eliminate valvular regurgitation, and restore ventricular geometry) [4].

This chapter details heart transplant procedures with emphasis on the complications specific to heart transplant patients and postoperative management.

Donor and recipient matching

Prospective recipients and donors must be ABO blood type compatible. They should be size matched, although differences of up to 20% may be tolerated. Recent data suggest that size mismatched organs are a risk factor for recipient mortality [5]. In recipients with an elevated panel reactive antibody (PRA), a cross-match should be performed with the prospective donor. A positive cross-match increases the likelihood of hyperacute rejection, and transplanting the organ should be avoided [3]. Generally, the practice of transplanting smaller female donor hearts into larger male recipients has resulted in poorer

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outcomes following cardiac transplantation [6]. In patients with elevated pulmonary artery pressures, attempts should be made to oversize the donor organ, to avoid post-transplant right ventricular failure [7].

Recipient operative technique

Generally heart transplant is performed as an orthotopic procedure. Heterotopic transplantation is reserved for cases in which the recipient has significant pulmonary hypertension or there is a marked size mismatch between recipient and donor.

There are several techniques of orthotopic heart transplantation. The biatrial technique, also referred to as the standard technique, involves excising the recipient heart at the midatrial level and sewing the corresponding anastomoses between the donor and recipient left atrium, right atrium, aorta, and pulmonary artery. An important modification of this technique allows for the incision in the donor heart's right atrium to extend from the opening of the IVC into the base of the right atrial appendage, rather than into the SVC. This modification helps avoid the region of the sinoatrial node and its blood supply.

Other techniques include the bicaval and total technique, which allow improved preservation of the atrial geometry. In the bicaval technique, separate SVC and IVC anastomoses are performed. In the total technique, separate SVC, IVC, right pulmonary vein, and left pulmonary vein anastomoses are completed. With all transplant techniques, the surgeon must meticulously pay attention to both vessel length, as well as the operative technique, to avoid vessel stenosis or kinking, that is, SVC stenosis (SVC syndrome) or PA kinking (RV failure).

The majority of transplant centers report that they utilize the bicaval technique most frequently. Although no large prospective randomized trials have been performed demonstrating its improved efficacy compared to the biatrial technique, multiple small studies have shown improved atrial function, decreased atrioventricular valvular insufficiency, and decreased sinus node dysfunction and subsequent pacemaker requirement [8–10].

Recipient postoperative management

After initial stabilization in the operating room, the patient is transferred to the intensive care unit. The patient remains mechanically ventilated with continuous monitoring of the ECG, arterial blood pressure, pulse oximetry, central venous pressure, urine output, temperature, and chest drain output. In some cases, a pulmonary artery catheter is also used to assess hemodynamics.

Generally, the patient is extubated when alert and hemodynamically stable, typically within 24 hours after transplant. Inotropic support is weaned over the first few postoperative days. Invasive catheters are removed as soon as possible to prevent line sepsis. Drains are removed when drainage has fallen to less than 25 mL/h. The temporary epicardial pacing wires, if placed during

the implantation procedure, are removed approximately 1 week after transplantation.

Complications

Post-transplant complications can be divided into three groups: (i) immediate, (ii) early (less than 30 days after transplant), and (iii) late (greater than 30 days after transplant).

Immediate

While most patients have uncomplicated postoperative courses, early complications include: (i) bleeding, (ii) hyperacute rejection, (iii) primary graft nonfunction, (iv) right ventricular failure, and (v) sinoatrial node dysfunction.

Significant hemorrhage occurs in 3–4% of cases, and it may require surgical re-exploration. The routine use of heparin-coated CPB circuits may reduce the incidence of postoperative bleeding [11]. The duration of bypass and previous sternotomy are risk factors for excessive bleeding, while preoperative anemia, renal insufficiency, previous sternotomy, and bypass duration are risk factors for intraoperative transfusion. The immunosuppressive effects of blood transfusion have been shown to decrease the incidence of acute rejection after transplant in several small series [12]. However, the overall mortality increases twofold in patients that receive blood transfusions during cardiac surgery [13].

Hyperacute rejection is a form of humorally mediated rejection and is largely preventable. It occurs when the recipient has preformed antibodies to the donor organ. These preformed antibodies result in activation of both inflammatory and coagulation cascades. Possible consequences include graft vessel thrombosis and subsequent heart failure. In general, hyperacute rejection can be prevented by proper ABO matching. An elevated PRA is also a risk factor for hyperacute rejection, and recipients with an elevated PRA must undergo cross-matching of donor lymphocytes with recipient serum.

Primary graft nonfunction is a rare but severe complication after heart transplantation, defined as circulatory insufficiency immediately after transplantation. Risk factors for the development of graft nonfunction include prolonged donor ischemia, inadequate donor preservation, and recipient pulmonary hypertension [14]. Importantly, more common causes of depressed myocardial function include hypovolemia, cardiac tamponade, sepsis, and arrhythmias. In the most severe situations, ventricular assist device placement or retransplantation may become necessary, but these procedures are associated with extremely high mortality rates [1].

Right heart failure may occur when a recipient has an elevated preoperative pulmonary vascular resistance (PVR). This complication usually presents within the first few hours post-transplant. Other causes of right heart failure include technical failures, such as kinking of the pulmonary artery

anastomosis. Intraoperative TEE should be performed routinely to assess right ventricular function and anastomosis quality [15]. Treatment options include surgical revision if a technical failure is present. Medical treatment consists of inotropic support, pulmonary vasculature dilatation (sodium nitroprusside, inhaled nitric oxide (NO)), and hyperventilation (goal CO_2 approximately 30). Refractory right heart failure may require placement of a right ventricular assist device.

Cardiac arrhythmias frequently occur in the early postoperative period. Sinoatrial node dysfunction may be secondary to a technical complication, as previously discussed. Junctional rhythm is the most common arrhythmia post-transplant. Because the transplanted heart is denervated, the cardiac output is heart rate dependent. Therefore, the heart rate should be maintained between 90 and 110 beats per minute with either chemical assistance (isoproteronol, dopamine) or pacing, if necessary. Fewer than 5% of transplant patients have permanent sinus node dysfunction, and this number should be reduced with the bicaval technique [16, 17].

Early postoperative complications

Infection

Due to maintenance immunosuppression, transplant patients are at increased risk of infection. Infection is associated with nearly 40% of late transplant patient deaths [1]. The timing of the infectious process helps to predict the source. Typically, early infections are bacterial in nature, occur in the first 3 months after transplant, and are easily treatable. These infections usually present as pneumonia, urinary tract infections, and line sepsis. Typical pathogens include *Pseudomonas aeruginosa*, *Staphylococcus aureus*, *Enterobacteriaceae*, and *enterococci*. Late infections are more likely to occur with increases in immunosuppression. They are typically caused by opportunistic pathogens including viruses, protozoa, and fungi, and these are discussed more fully below.

Virus

The most common and clinically significant viral pathogen is cytomegalovirus (CMV). Transplant patients are at increased risk of acquiring CMV since their immunosuppressive medications impair the cellular immunity required for clearing the infection. Patients typically contract CMV within 1–4 months after transplant. The two patient populations at highest risk of acquiring CMV infections are the seropositive patient and the patient being treated with antilymphocyte antibodies. Seronegative patients that receive organs from seropositive donors can also contract CMV [18].

CMV can result in two types of clinically significant infections: a mononucleosis-like syndrome or a tissue invasive infection. The most common sites of infection are lung, liver, and the gastrointestinal tract. Less common sites include the retina and skin. Diagnosis is made with a

quantitative polymerase chain reaction (PCR) test, or by direct culture of infected tissue. CMV treatment includes ganciclovir and hyperimmune globulin. Serologically mismatched patients should also receive a prophylactic combination of these two drugs. Serologically positive patients should also be prophylactically treated to prevent reactivation. The treatment course varies among centers from weeks to months post-transplant.

Protozoa

Although protozoal infections are rare, the two major protozoal pathogens include *Pneumocystis carinii* and *Toxoplasmosis gondii* [19]. *P. carinii* typically presents with pulmonary infections and is diagnosed by bronchoalveolar lavage. All patients should be treated with prophylactic sulfa and trimethoprim, or aerosolized pentamidine (for sulfa-allergic patients). *Toxoplasmosis* typically occurs in the serologically mismatched patient. In these cases, recipients should be treated with prophylactic pyrimethamine.

Fungi

Fungal infections are also rare, but when present, they are a significant cause of mortality and morbidity after heart transplantation. The most common pathogens include *Candida albicans* and *Aspergillus*. Treatment consists of fluconazole, itraconazole, or amphotericin B depending on sensitivities [20].

Acute rejection

Acute rejection is a cell-mediated immune response to the donor heart that begins in the early postoperative course. It is experienced by the majority of heart transplant patients. The risk of acute rejection is highest during the first 6 months after transplant [1]. There is a mortality risk associated with each episode of acute rejection. The frequency and severity of acute rejection episodes correlate with the development of cardiac allograft vasculopathy (CAV), which can lead to graft failure and patient death. The risk factors for acute rejection during the first transplant year include young age, female gender, female donor, positive CMV serology, prior infections, OKT3 induction, as well as shortened frequency between acute rejection episodes. After the first year, risk factors include frequency of rejection episodes during the first year and positive CMV serology.

The clinical presentation of acute rejection varies widely. Some patients remain asymptomatic, while others have vague nonspecific complaints. Rarely, acute rejection presents as severe hypotension and circulatory collapse. Because the clinical course is so varied, the gold standard for diagnosis is an endomyocardial biopsy. These biopsies are performed periodically as part of a routine post-transplant surveillance protocol, as well as when clinical suspicion dictates. If the patient remains free from acute rejection for 6 months, sampling occurs in 3-month intervals. Because acute rejection often occurs in a randomized pattern in the heart, four to six samples should be obtained.

Table 21.1 ISHLT standardized cardiac biopsy grading [47].

	Grade	*Severity*	*Endomyocardial biopsy*
AR	0 R	None	
	1 R	Mild	Interstitial and/or perivascular infiltrate with up to 1 focus of myocyte damage
	2 R	Moderate	Two or more foci of infiltrate with associated myocyte damage
	3 R	Severe	Diffuse infiltrate with multifocal myocyte damage +/− edema, +/− hemorrhage, +/− vasculitis
AMR	0		Negative for acute AMR
	1		Positive immunofluorescence or immunoperoxidase staining for AMR (+CD68, +C4d)

AR, acute cellular rejection; AMR, acute antibody-mediated rejection.

Endomyocardial biopsy is the single most important cause of significant tricuspid regurgitation after heart transplantation due to anatomic disruption of the tricuspid valvular apparatus [21]. A standardized grading system for the severity of acute rejection has been developed by the International Society for Heart and Lung Transplant, and was recently updated (Table 21.1).

Because endomyocardial biopsies are both invasive and costly, new noninvasive techniques are being developed and refined. Magnetic resonance imaging (MRI), wall motion analysis with tissue Doppler imaging, and ventricular evoked response amplitude assessment are imaging techniques currently being evaluated as potential noninvasive techniques [22, 23]. Identification of rejection blood markers and gene array analysis of circulating lymphocytes are other noninvasive techniques under development [24, 25].

Once a histological diagnosis of acute rejection is made, treatment consists of increased immunosuppression. For low-grade rejection, increased maintenance immunosuppression is usually adequate. For higher grade episodes, pulsed high dose corticosteroids may be necessary [26]. Regardless, endomyocardial biopsy is performed 2 weeks after treatment to determine treatment efficacy. If rejection persists, then patients may be treated with antilymphocyte antibody preparations or by conversion of maintenance immunotherapy to a different regimen [27]. In the rare instance of refractory acute rejection, total lymphoid irradiation [28], plasmapheresis [29], and conversion of azathioprine to cyclophosphamide or methotrexate have been used [25] (Figure 21.1).

Antibody-mediated rejection

Antibody-mediated rejection (AMR), triggered by donor-specific antibodies, has emerged as a major cause of allograft loss and typically is unresponsive to conventional immunosuppressive regimens, thus propagating a necessity for

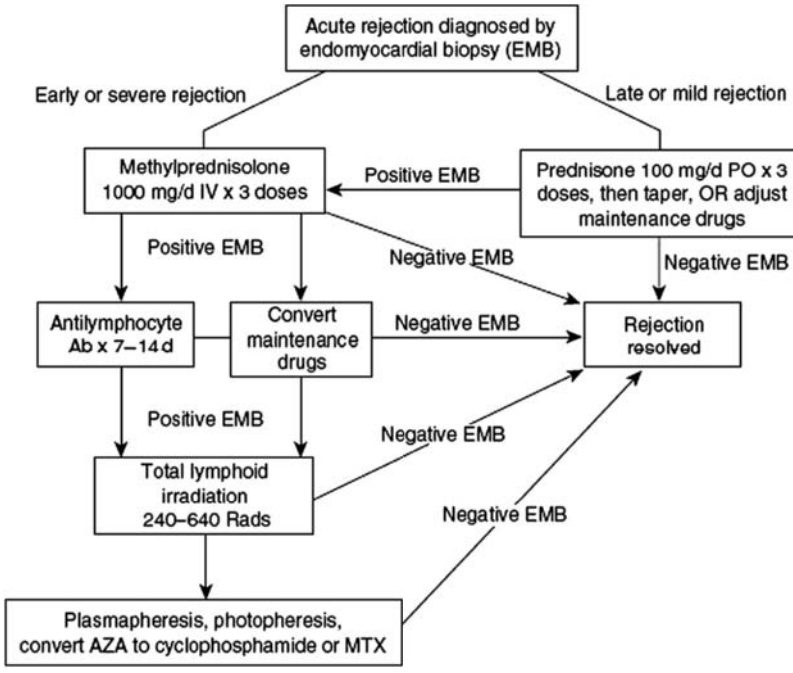

Figure 21.1 Treatment algorithm for acute rejection in heart transplant recipients [48].

intense research both in evaluation, diagnosis, and treatment. Patients with AMR are more susceptible to developing CAV and carry a significant mortality rate (17%) in the early post-transplant period [30]. Long-term survival was also found to be decreased in recipients with a diagnosis of AMR. Taylor *et al*. found that allograft 3-year survival was 57% in patients with AMR and the risk of graft loss and dysfunction was approximately twofold greater than recipients with cellular rejection only [31].

Acute AMR is estimated to occur in 15% of cardiac recipients. The combined presence of both acute AMR and cellular rejection was reported in 23% of biopsy specimens in 587 cardiac recipients [31]. AMR manifests clinically as early as 2–7 days if the recipient has been presensitized with donor HLA, or as late as 1 month post-transplant and may be associated with a rise in donor-specific antibodies [31]. For those patients experiencing early AMR, approximately 70% will develop allograft dysfunction [32]. If AMR occurs late, several months to years, graft dysfunction is much less common at 13%.

The incidence of AMR is increased in cardiac recipients with prior sensitization to HLA antigens. Due to increasing number of cardiac retransplantations and patients receiving LVADs, the proportion of potential recipients sensitized while on the waiting list is expanding. Causes of preformed antibodies are transfusions, previous transplantation, and pregnancy, with the latter being a major cause of allosensitization in females. There is also an association of

AMR with patients who develop de novo antibodies to HLA antigens post-transplant.

In 2004, the ISHLT assembled an udated version of the grading system for AMR known as the Revision of the 1990 Working Formulation for the Standardization of Nomenclature in the Diagnosis of Heart Rejection [33]. AMR is classified as changes in myocardial capillaries as seen by a combination of H&E and immunohistochemistry features. Demonstration of positive antidonor antibodies along with clinical and histologic findings is recommended for the diagnosis of acute AMR. It remains controversial as to whether the absence of cellular rejection be necessary for the diagnosis. As noted previously, a moderate amount of patients with acute AMR will also have a diagnosis of acute cellular rejection. The 2004 ISHLT Revision Committee also recognized acute AMR as a clinical diagnosis although there still remains a significant amount of variability between transplant centers [33].

The exact treatment regimen for recipients with AMR continues to be variable between transplant centers. However, the treatment for acute AMR does rely on the same principles that include aggressive hemodynamic management along with augmentation of the immunosuppressive regimen that maximizes the effort against circulating donor-specific antibodies as well as lessens B cell activity. As discussed previously, plasmapharesis, IVIG, both plasmapharesis and IVIG, augmentation of immunosuppressive therapy, cytolytic therapy, and steroids have all been utilized (Figure 21.2).

Pericardial effusion

Pericardial effusions occur in up to 35% of patients receiving heart transplantation, and they usually are not clinically significant. The etiology is unclear. However, it appears to be related to immunosuppressants, epicardial inflammation, and donor-recipient weight mismatch. Multiple studies have shown that there is no correlation between pericardial effusions and acute rejection. In rare instances pericardial effusions can lead to cardiac tamponade, and thus do require close monitoring with serial echocardiography [34].

Renal failure

Acute renal failure in the early postoperative period after cardiac transplant is very common. However, only a small percentage of patients will progress to chronic renal failure. Unfortunately, those that do progress have an increased mortality. Risk factors for acute renal failure after transplant are preoperative renal insufficiency, elevated cyclosporine levels, cold ischemia time, age, postoperative hypotension, and decreased postoperative cardiac output [35]. Cyclosporine nephrotoxicity occurs in a dose-dependent manner and can be attributed to the peak serum levels. Some centers utilize antithymocyte globulin perioperatively to prevent cyclosporine toxicity [36]. Renal function may improve by stopping or decreasing cyclosporine.

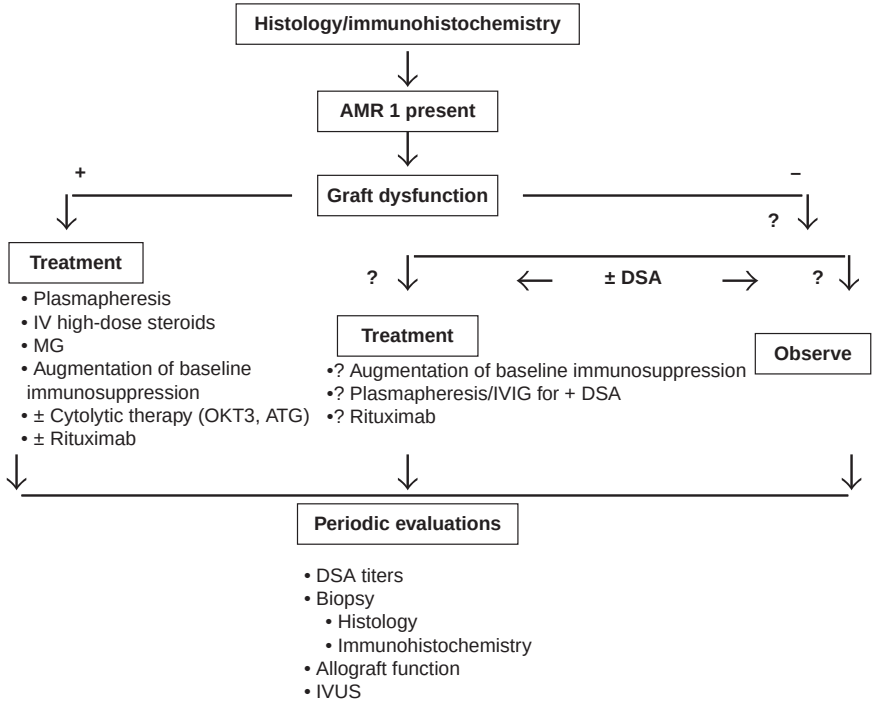

Figure 21.2 Algorithm for treatment of acute antibody-mediated rejection in cardiac transplant patients[49].

Late postoperative complications

Chronic rejection

Chronic rejection, also known as CAV, is a disease process that results in diffuse narrowing of both the large and small caliber vessels in the graft. The narrowing consists of a fibrous neointimal hyperplasia. It is a distinct entity from atherosclerotic lesions, although both may be present in some patients. The long-term survival of heart transplants is limited by CAV development [1].

The pathogenesis of CAV is poorly understood. Research has shown that there are both alloantigen-dependent and independent processes involved. Most investigators agree that the initiating event may be "injury" to the vascular endothelium. Alloantigen-independent events that have been implicated include graft ischemia time, oxidative stress from ischemia and reperfusion injury, infections (CMV), and recipient metabolic syndromes (i.e., hyperlipidemia and diabetes mellitus). Alloantigen-dependent events involve the role of both acute cellular and humoral immunity.

The clinical manifestation of CAV is nonspecific. Patients can present with arrhythmias, myocardial infarction, sudden death, or congestive heart failure

secondary to left ventricular dysfunction. However, classical angina symptoms are rare because the graft is denervated.

Most transplants centers screen transplant recipients for CAV on at least a yearly basis with coronary angiography. Coronary angiography is neither specific nor sensitive for CAV, and it tends to underestimate the extent of disease. Dobutamine stress echocardiography or stress thallium scanning may also be used for routine screening [37]. Intracoronary ultrasound is a more sensitive procedure and allows for quantification of the intimal area, lumen area, and plaque morphology [38].

Unfortunately, treatment for CAV is limited. Due to the diffuse nature of the disease and the immunological basis, bypass grafting is commonly not an option. Ultimately, severe disease will lead *to* ischemic graft failure and require retransplantation in the majority of cases. Angioplasty and stenting can be used on focal stenosis. However, the progressive nature of the disease process will commonly result in restenosis [39].

Due to the lack of treatment options, the best treatment is preventative. Alloantigen independent risk factors, such as hyperlipidemia and diabetes mellitus, should be controlled with medication. Patients should be treated prophylactically for CMV infections. In experimental animal models, regulation of ischemia and reperfusion injury or augmentation of nitric oxide activity can also lead to CAV prevention, but these therapies are not currently clinically applicable [40, 41].

Tricuspid regurgitation

Tricuspid regurgitation is seen in approximately 20% of all cardiac transplant recipients, but only 5% of those develop moderate to severe regurgitation by 5 years. The development of TR has been attributed to (i) distortion of the tricuspid annulus in the right atrial anastomosis, (ii) ischemic injury, (iii) biopsy-induced injury, (iv) donor-recipient size mismatch, and (v) endocarditis. Multiple studies have demonstrated that the development of TR is independent of pulmonary hypertension [42]. The majority of patients with TR will remain clinically asymptomatic. Those that progress to severe TR can have symptoms of right heart failure, including fatigue, lower extremity edema, liver congestion, and decreased renal function. Medical management with diuretics is the preferred treatment for TR after transplantation. For refractory cases of annular dilation, valve repair with annuloplasty is preferred. If the TR is secondary to biopsy-related injury then replacement with a bioprosthetic is frequently required [43].

In order to prevent the number of tricuspid valve injuries secondary to EMB, development of alternative surveillance methods has been proposed. The use of echocardiography, gene expression profiling, and intramyocardial electrocardiography all show promise. In addition, when EMB is performed, it is recommended to use a longer bioptome sheath at the time of biopsy to decrease injury [21].

Constrictive pericarditis

Although uncommon, refractory heart failure in a postoperative heart transplant recipient can signify the development of constrictive pericarditis. The development of pericarditis postoperatively typically occurs in the setting of pericardial irritation secondary to postoperative bleeding. Due to the lack of specific diagnostic maneuvers, the diagnosis typically is determined through right and left heart catheterization. If medical management fails, pericardiectomy is required. There is a 10% mortality associated with this procedure post-transplant. Despite surgical intervention, there is a subset of patients who develop a restrictive myopathy and will not respond to operative interventions [44].

Immunosuppression

In addition to careful monitoring of cardiac function in the immediate postoperative course, the immune system must continue to be suppressed. In most cases, immunosuppression is initiated intraoperatively with intravenous methylprednisolone. This is continued postoperatively with a combination of oral and intravenous medications. Because the risk for acute rejection is highest during the first 6 months after transplant, the immune system is most suppressed during this time. If the patient does not have any episodes of rejection within the first 6 months, the immunosuppression medications can be decreased gradually. There are three general methods employed to prevent rejection of the donor heart: (i) multi-drug immunosuppression regimens; (ii) IL-2 signaling blockade; and (iii) cytolytic induction therapy.

Most centers have adopted multi-drug immunosuppression regimens, which typically consist of a triple drug combination of a calcineurin inhibitor, an antiproliferative agent, and corticosteroids. Few randomized clinical trials have been performed comparing different immunosuppressive protocols in heart transplantation, thus immunosuppressive practices vary widely among centers.

Multi-drug immunosuppression targets multiple sites in the immune cascade and acts synergistically to minimize the dose-dependent toxicity to the recipient. Calcineurin inhibitors block the activity of calcineurin, a calcium- and calmodulin-dependent phosphatase that is required for early T lymphocyte activation and interleukin-2 formation. Antiproliferative agents inhibit lymphocyte replication through a variety of mechanisms. Azathioprine inhibits the de novo and salvage pathways for purine biosynthesis. Mycophenolate mofetil (MMF) inhibits the de novo synthesis of guanine nucleotides. MMF is thought to have greater selectivity than azathioprine because activated lymphocytes use the de novo pathway predominantly. Corticosteroids inhibit lymphocyte proliferation by inhibiting macrophage production of cytokines, including IL-1 and IL-6.

Although the side effects of these drugs are minimized when used in combination, they can still occur. Cyclosporine can cause nephrotoxicity, neurotoxicity, hypertension, hyperlipidemia, hirsutism, and gingival hyperplasia.

Tacrolimus is also nephrotoxic and neurotoxic and has been associated with glucose intolerance and diabetes mellitus. Cyclosporine and tacrolimus are metabolized by the liver and induce upregulation of the p450 system. Azathioprine and MMF cause dose-dependent bone marrow suppression. Corticosteroids are associated with a myriad of side effects, including poor wound healing, development of cushingoid features, hypertension, diabetes mellitus, osteoporosis, and peptic ulcer disease.

Another method for preventing rejection is IL-2 signaling blockade. Rapamycin, also known as sirolimus, has been used successfully in renal and liver transplantation and is now being used as a component of triple therapy for heart transplants. It inhibits the mammalian target of rapamycin (mTOR), thus blocking IL-2 signaling pathways. Rapamycin has also been shown to inhibit CAV [45]. IL-2 receptor antagonists and humanized antibodies to the IL-2 receptor result in the destruction of activated T lymphocytes expressing IL-2 receptors. Short-term studies for receptor blockade also demonstrate a decrease in the frequency and severity of acute rejection in the first transplant year, but definitive long-term studies are ongoing to determine if there is a survival benefit, and if there is an increased malignancy risk. The early results of these long-term studies demonstrate a trend towards decreasing CAV development.

Many centers also employ cytolytic induction therapy to rapidly deplete lymphocytes in heart transplant recipients. Because the induction results in immediate and profound immunosuppression, the initiation of maintenance immunosuppression can be delayed until the recipient has stabilized and then continues over a 3–10 day period. Induction is performed with antilymphocyte antibodies, and multiple preparations are available, including antithymocyte globulin (ATG), OKT3, and IL-2 receptor antagonists. ATG is a polyclonal antibody that results in rapid cytolytic depletion of T lymphocytes. OKT3 is a mouse monoclonal antibody directed against the CD3 receptor of human T lymphocytes. Induction therapy is associated with at least four complications. First, initial doses of induction therapy can be associated with a "cytokine release syndrome," resulting in fever, chills, hypotension, and bronchospasm. For this reason, patients receiving induction should be premedicated with acetaminophen, antihistamines, and corticosteroids. Second, because the induction agents are raised in animals, patients may develop neutralizing antibodies. This may prevent multiple or prolonged dosing. Third, induction therapy may increase the incidence of infectious complications and post-transplant lymphoproliferative disorder (PTLD). Lastly, some studies suggest that induction may not decrease the incidence of acute rejection, but only delay onset of the first episode.

Two disease processes with links to immunosuppression deserve special mention: (i) neoplasm and (ii) diabetes mellitus. Due to chronic immunosuppression, heart transplant recipients are at increased risk of developing neoplasms that significantly affect long-term survival. Of the three major categories of neoplasms—skin cancers, B-cell lymphoproliferative disorders

(PTLD), and solid organ tumors—only skin cancers and PTLD tumors are seen with increased frequency in heart transplant patients. The B-cell lymphoproliferative disorders range from hyperplasia to lymphomas, and more than 95% of PTLD neoplasms are related to Epstein Barr Virus (EBV) infections. By the seventh year after transplant, approximately 25% of patients are expected to develop one of these neoplasms [1]. It is suspected that this increased incidence of neoplasm occurs in transplant patients because of their suppressed immune system. Typical treatment for skin cancers consist of surgical excision and for PTLD includes immunosuppression reduction. If necessary, other conventional treatment for lymphomas may be necessary, including chemotherapy, radiotherapy, and immunotherapy.

Approximately 30% of heart transplant recipients will develop diabetes mellitus within 5 years of transplant [1]. Risk factors such as preoperative glucose intolerance, obesity, and age predispose transplant patients to new onset diabetes after transplant. Approximately 75% of cases are due to steroids or calcineurin inhibitors. Recent studies have shown that tacrolimus increases the development of diabetes compared to cyclosporine. Although the direct impact of diabetes on cardiac transplant survival is not known, there is evidence linking the development of chronic rejection to diabetes. Post-transplant diabetes can be managed similarly to patients with type 2 diabetes for a goal A1c $< 6.5\%$ and premeal blood glucose levels below 120 mg/dl or postmeal levels below 160 mg/dl.

Long-term results in cardiac transplantation

Analyzing data from 1982 to 2005, the ISHLT has published survival rates in heart transplant recipients. They have found 1-year, 5-year, 10-year, and 15-year survival rates of 86%, 70%, 51%, and 30%, respectively [1]. Patient half-life (i.e., time to 50% survival) is 10 years. Survival rates have been improving over time as seen by the 86% 1-year survival rate for patients transplanted from 2002 to 2005. The Stanford University Transplant Group has demonstrated slightly higher patient survival data compared to the national average with 1-year, 5-year, and 10-year patient survival rates of 89%, 77%, and 74%, respectively.

Several risk factors for 1-year mortality have been neutralized or mitigated, and they include repeat transplantation, IABP at time of transplant, PRA $> 10\%$, female donor, HLA-B or—DR mismatches, and donor history of hypertension. The 2007 ISHLT registry lists the following as risk factors for 1-year mortality for transplants performed from 2002 to 2005: mechanical assistance (e.g., extracorporeal membrane oxygenation (ECMO) and VAD), underlying diagnosis of congenital heart disease, recipient history of the following: insulin-dependent diabetes, ventilator assistance, dialysis, prior CVA, previous pregnancy, prior infection requiring IV drug therapy within 2 weeks of transplant, and prior sternotomy. Significant 5-year mortality risk factors included CAV within the first year after transplant, rejection within

the first year after transplant, retransplantation, pretransplant diabetes, and treated infection during transplant admission. Significant continuous risk factors have remained constant over the years and include recipient weight, recipient age, donor age, donor heart ischemic time, center volume, PAD pressure, PVR, pretransplant bilirubin, and pretransplant creatinine [46].

Approximately 40% of patients are hospitalized in the first year after transplant, often for treatment of rejection or infection. By the second year after transplant, only 20% are hospitalized. The vast majority report good functional status after transplantation, yet less than 40% of heart transplant recipients return to work after transplantation.

Summary

The perseverance of early pioneers in heart transplantation has led to its current position as a mainstay of therapy for heart failure. For carefully selected patients, heart transplantation offers markedly improved survival and quality of life. However, major and minor complications are still prevalent, and further research in developing novel immunosuppressive regimens and understanding the immunobiology of cardiac allograft rejection is vital. In the years to come, limitations in donor organ availability and preservation will be important areas for study and improvement. Newer, more technologically advanced mechanical assist devices, stem cell transplantation, and improved medical therapy are research areas that are growing exponentially and should continue to be explored as alternatives to transplantation in patients with heart failure to help minimize overall complications associated with cardiac transplantation.

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CHAPTER 22

Assist Devices

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Introduction

Heart failure continues to be an ever-growing public health concern facing our country today. Approximately 5 million people are affected, with over 500 000 new cases diagnosed annually. Economically, this represents over 30 billion dollars in health care spending in the United States each year [1–4]. The continued aging of the population has contributed to the increasing incidence and prevalence of heart failure. Despite advances in the understanding of the neurohormonal changes involved in the progression of heart failure and improvements in medical management, the natural history of the disease dictates a dismal prognosis. Cardiac transplantation has been regarded as the gold standard treatment for end-stage heart failure. However, over the past decade, the number of transplants performed worldwide has remained between 3000 and 4000 annually, with a decreasing trend noted in recent years [5]. The limited supply of donor organs and strict recipient selection criteria have relegated transplantation as a viable option for a minority of patients needing cardiac replacement therapy. Cardiac transplantation has limited impact on the epidemiology of heart failure [6].

Due to the relative shortage of donor organs, ventricular assist device (VAD) therapy has emerged as an important modality in the treatment of end-stage heart failure, both as a bridge to transplantation and as permanent or "destination" therapy for patients who are not candidates for cardiac transplant. The feasibility of a mechanically based approach to the treatment of end-stage heart failure was validated by the REMATCH trial in 2001 [7]. This prospective randomized trial demonstrated a marked survival benefit in patients receiving mechanical ventricular assistance for the treatment of end-stage heart failure when compared to medical management alone. At the same time, the limitations of device technology were highlighted by the incidence of adverse events related to mechanical support, such as infection, device failure, and thromboembolic events. This chapter will discuss important factors in risk

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assessment and patient selection, as well as the prevention, diagnosis, and treatment of the most common complications associated with assist device therapy.

Patient selection/risk stratification

With advances in device technology and improvements in patient selection criteria, the indications for mechanical circulatory support continue to evolve. In general terms, patients considered for mechanical circulatory support can no longer sustain adequate systemic oxygen delivery to maintain normal end organ function despite maximal medical therapy. The decision to implement mechanical circulatory support must be made with due consideration of the ultimate goal of therapy. Devices can be used as a bridge to transplantation, as a bridge to myocardial recovery, or as destination therapy in patients not eligible for cardiac transplantation.

Appropriate patient selection represents one the most critical determinants of successful outcomes with VAD therapy. The operative risk of device implantation must be weighed against the potential lifestyle and survival benefit that might be expected with mechanical support. Patient selection criteria must not be so stringent as to exclude ill patients that may benefit from device therapy, while at the same time avoiding high mortality rates by the inclusion of patients that have a prohibitive risk. Risk stratification systems such as the Heart Failure Survival Score and the Seattle Heart Failure Score are useful in identifying patients who may benefit from support with a VAD [8, 9]. VADs have been used to treat a wide variety of disease processes leading to both acute and chronic forms of heart failure including cardiogenic shock associated with myocardial infarction, postcardiotomy shock, myocarditis, and chronic ischemic and nonischemic cardiomyopathies.

Several reports have sought to identify significant preoperative variables that may predict risk and impact outcomes. The revised Columbia screening scale published in 2003 offers a way of stratifying the risk for LVAD therapy based on several clinical factors including the following: mechanical ventilation, postcardiotomy failure, prior LVAD insertion, CVP $>$ 16 mm Hg, and prothrombin time $>$ 16 seconds [10]. Each factor is given a relative weight, with a cumulative score of >5 predicting an operative mortality of 46% versus a mortality rate of 12% for a score ≤ 5. This scoring system was a revision of a prior scale developed in conjunction with the Cleveland Clinic Foundation [11]. The revised scoring scale was the result of an analysis of 130 patients undergoing implantation of the Heartmate-vented electrical device. In the revised scoring scale, preoperative oliguria (urine output $<$ 30 cc/h) and reoperative surgery were not statistically significant factors in predicting postoperative mortality, as they were in the old model. McCarthy and colleagues previously reported the results of 100 patients undergoing LVAD implantation [12]. In this group of patients, preoperative factors that increased the risk of death by univariate analysis included the need for mechanical ventilation or

extracorporeal membrane oxygenation (ECMO), low pulmonary arterial pressures, and elevations in bilirubin, blood urea nitrogen, and creatinine. Deng *et al*. reported the results of 464 patients undergoing implantation of the Novacor LVAS. Sepsis associated with respiratory failure, preoperative right heart failure, age > 65 years, acute postcardiotomy state, and acute infarction were independent risk factors for death by multivariate analysis [13].

More contemporary risk models include those by Lietz *et al*. and Matthews *et al.* [14, 15]. The risk model by Lietz and colleagues specifically looks at early survival in patients undergoing LVAD implantation for destination therapy. In this study, predictors of 90-day in-hospital mortality included the following: platelet count $\leq 148 \times 10^3/\mu L$, serum albumin ≤ 3.3 g/dL, INR > 1.1, mean pulmonary pressure ≤ 25.3 mm Hg, vasodilator therapy at time of implantation, AST > 45 U/dL, hematocrit < 34%, BUN >51 U/dL, and lack of intravenous inotropic support. The Matthews risk score was developed to assess the risk of RV failure but additionally describes the risk of early mortality following LVAD implantation. Patients identified to be at high risk for postoperative RV failure in this model were also found to be at increased risk for postoperative death following LVAD implantation.

Several factors have been shown to be associated with poor clinical outcomes following device implantation. These include severe malnutrition, morbid obesity, severe irreversible hepatic disease, renal failure requiring hemodialysis, severe chronic obstructive pulmonary disease, and a documented history of noncompliance. Although inclusion criteria for mechanical support have expanded in recent years, there still exist generally agreed upon contraindications for device implantation. Patients with irreversible end organ damage, particularly renal, hepatic, or respiratory failure, uniformly demonstrate poor clinical outcomes. Severe and unrecoverable neurologic injury with cognitive deficit also represents a contraindication to device implantation. Systemic sepsis or bacteremia poses a high risk of device contamination after implantation and should be controlled prior to LVAD insertion.

The timing of intervention is also an important determinant of clinical outcomes. Optimization of the patient's clinical status with diuresis, correction of coagulation abnormalities, pulmonary rehabilitation, and intra-aortic balloon counterpulsation are potentially important therapeutic interventions, but they should not delay institution of support in critically ill patients with severe ventricular failure and ongoing end-organ malperfusion. In the acute setting of postcardiotomy shock, data from the Abiomed registry demonstrated that delays in instituting mechanical support beyond 6 hours led to a marked increase in mortality [16, 17]. Urgency of device implantation also has an impact on overall survival. Deng and coworkers reported the results of patients undergoing device implantation for bridge to transplantation, showing a decreased rate of survival to transplantation in those receiving LVADs for emergent indications such as acute myocardial infarction, postcardiotomy failure, and acute heart failure when compared to patients receiving devices on an elective basis [18]. Data from the Interagency Registry for Mechanically

Assisted Circulatory Support (INTERMACS) similarly has shown lower survival for patients in cardiogenic shock at the time of device implantation [19].

Specific complications

Device failure

Device failure is an ever-present concern in patients with mechanical circulatory assistance. Device durability and freedom from device failure are critical factors in establishing mechanical support as a feasible option for providing long-term support and destination therapy. Modes of mechanical failure are specific to the particular type of device technology employed. First-generation LVADs such as the Heartmate XVE (used in the REMATCH trial) utilize pusher plate technology to generate pulsatile flow through displacement of blood volume. This necessitates the devices to be somewhat large to accommodate the pumping chamber, requires several moving and contacting parts, as well as inflow and outflow valves to maintain unidirectional flow. In the REMATCH trial, device failure was the second most common cause of death behind sepsis [7]. While 1-year freedom from device failure and replacement was 87%, this dropped off to 37% by the second year [7, 20]. Device failure can occur in any one of the components of the system. These include the inflow and outflow conduits, the pumping chamber, or the external components of the system. Inadequate device flows can also be the result of mechanical problems such as inflow cannula obstruction or malposition, outflow graft kinking, or cardiac tamponade.

The need to improve device durability and freedom from device failure has been a major impetus for the evolution of device technology. Second-generation LVADs utilize an axial flow design with a rotating impeller to provide continuous nonpulsatile blood flow without the need for inflow or outflow valves. Compared to pulsatile VADs, these devices offer the advantage of being smaller in size, and they have fewer moving parts and contact bearings with potentially enhanced durability. A recent trial reported the results of 133 patients undergoing implantation of the Heartmate II axial flow LVAD as a bridge to transplantation [21]. In this series, there were no primary pump failures. Five patients did require device replacement; two for pump thrombosis and three for complications related to surgical implantation. While continuous-flow devices may offer improved long-term durability, pump thrombosis is a potential mode of failure, and avoidance requires systemic anticoagulation. Although early concerns existed regarding the effects of nonphysiologic continuous blood flow, studies have shown no adverse impact on end-organ function or ventricular unloading and remodeling [22–24]. Newer or third-generation devices have become even smaller in size and utilize magnetic levitation technology or hydrodynamic suspension to achieve rotary blood flow with no contacting parts. The hope is to achieve even longer durability and freedom from device wear. Several third-generation devices are currently in clinical trials.

Device failure can be the result of malfunction of any of the external components. This includes the percutaneous lead, system controller, and power source. A recent medical device correction notice was issued by the Thoratec Corporation describing wear and fatigue of the percutaneous driveline in Heartmate II recipients, leading to device replacement in 27 patients. The probability of percutaneous lead damage requiring pump exchange was estimated to be 1.3%, 6.5%, and 11.4% at 12, 24, and 36 months, respectively [25].

Postoperatively, the diagnosis of device malfunction can be challenging. Modes of failure are dependent on the type of device used. A retrospective analysis of 1865 Heartmate LVAS implants identified inflow valve dysfunction, percutaneous lead breaks, diaphragm fractures, outflow graft erosion, and pump disconnect as sources of mechanical failure [26]. As clinical experience with individual devices accumulates, modes of failure that are amenable to design changes become apparent, allowing for device modification and improvement. Design alterations during and since the conclusion of the REMATCH trial in the Heartmate LVAD include a bend relief to prevent outflow graft kinking, modifications in the inflow assembly to facilitate valve replacement, and smaller size and greater compliance of the percutaneous driveline [26, 27]. Modifications in the controller software allow limitation of pump pressures, thereby reducing stress on bearings, the diaphragm, and inflow valve [20]. Newer second- and third-generation axial and centrifugal flow pumps attempt to address the shortcomings of first-generation devices with smaller sized pumping chambers and drivelines, fewer moving parts, valveless inflow and outflow conduits, transcutaneous energy sources, and, in the case of third-generation pumps, the use of magnetic levitation technology to eliminate contact-bearing moving parts, offering the hope of enhanced durability (Figure 22.1).

Knowledge of the monitoring parameters available for a device is essential for troubleshooting. For pulsatile pumps, excessively high beat and flow rates in an automatic setting may be an indication of inflow valve regurgitation or aortic insufficiency. High-pressure alarms with decreased flows in both axial and pulsatile pumps can be caused by outflow graft obstruction. Inflow valve obstruction due to thrombus or tissue ingrowth will lead to impaired device filling and low device output in the setting of poor ventricular decompression. For axial and centrifugal flow pumps, increases in the power consumption of the device may be an early indication of pump thrombus formation.

Cardiac catheterization as well as transesophageal echocardiography have both been described as useful tools for the diagnosis of device malfunction [28, 29]. In addition, CT angiography with 3-dimensional reconstruction can be useful, especially in the diagnosis of suspected outflow graft abnormalities (Figure 22.2). Slaughter *et al.* reported the use of acoustic signal monitoring as a reliable noninvasive way of identifying device end-of-life [30]. This study, which examined patients implanted with the Heartmate XVE pulsatile pump, may have future application to the axial and centrifugal flow pumps, allowing

Figure 22.1 The Heartmate XVE pulsatile LVAD (left) and the Heartmate II axial flow LVAD (right).

for elective device exchange prior to failure. In the event of device failure, some systems have backup support. For instance, the Heartmate LVAD, in the setting of electrical failure, can be driven by a pneumatic console. Some newer generation continuous-flow devices, however, lack this provision. In the event of device malfunction, the patient is dependent on their native ventricular function. Depending on the mode of failure, urgent reoperation and device replacement may be required.

Anatomic factors leading to device malfunction

Preoperatively, a thorough assessment of the patients native cardiac anatomy must be made. Certain anatomic factors must be considered and addressed at the time of LVAD implant to ensure adequate inflow and outflow and proper device functioning. Aortic insufficiency (AI) must be corrected at the time of LVAD insertion. After LVAD placement, AI may significantly worsen due to decompression of the left ventricle with a subsequent increase in the transvalvular gradient. Net forward flow and end-organ perfusion may be severely compromised with a continuous-flow loop of regurgitation from device outflow graft back to the ventricle. Aortic insufficiency can be managed either with suture coaptation of the aortic valve leaflets, bioprosthetic aortic

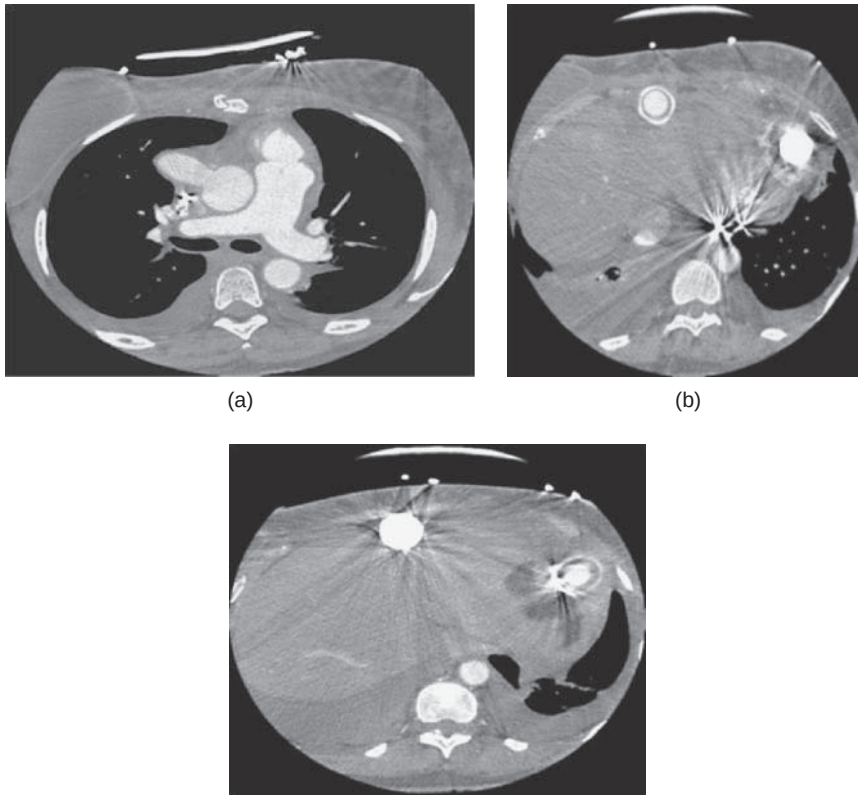

Figure 22.2 (a–c) CT scan demonstrating proper alignment of both inflow and outflow cannula without evidence of kinking or obstruction.

valve replacement, or patch closure of the outflow tract [31, 32]. In general, aortic stenosis does not need to be corrected since this has no impact on device performance.

Mitral regurgitation (MR) improves after LV unloading and usually does not need specific therapy in patients undergoing device placement. For patients who ultimately achieve myocardial recovery, consideration should be given to repair of significant MR at the time of device explant. In contrast, significant mitral stenosis will limit inflow into the device and must be corrected with bioprosthetic valve replacement or mitral valvuloplasty at the time of LVAD insertion.

While most agree that severe tricuspid regurgitation (TR) should be treated with valve repair or replacement, there is no clear consensus for the treatment of patients with mild to moderate TR. Some have advocated aggressive repair of moderate TR in order to optimize perioperative right ventricular function. With decompression of the LV and a subsequent decrease in left ventricular

end diastolic pressure and pulmonary pressures, however, TR in many cases does improve over time. Finally, every effort should be made to clearly identify a patent foramen ovale or any other source of intracardiac shunting. If left uncorrected, severe right to left shunting may occur after device initiation with subsequent postoperative hypoxemia.

Intraoperatively, although minor variations exist, the technique of device implantation can be grouped into a few common steps. These are (i) mediastinal exposure and creation of device pocket; (ii) outflow graft anastomosis to the ascending aorta; (iii) placement of device inflow usually from the left ventricular apex; (iv) de-airing of the device; (v) device actuation and weaning from cardiopulmonary bypass support. Meticulous attention to detail is necessary for proper device implantation and functioning.

With respect to inflow cannula placement, care must be taken to ensure appropriate placement at the left ventricular apex. Deviation medially into the septum or laterally into the ventricular free wall can result in inflow cannula obstruction and impaired device filling. Contact of the cannula with the free wall or septum may also lead to refractory ventricular arrhythmias postoperatively. When constructing the outflow graft, care must be taken when sizing the length of the graft to avoid excessive redundancy and the risk of kinking. An effort should be made to deviate the outflow graft away from the sternal midline to avoid injury upon sternal reentry for future cardiac procedures. In some cases, this may be facilitated by opening the right pleural space. The use of intraoperative transesophageal echocardiography (TEE) is invaluable for confirming evacuation of intracavitary air as well as identifying residual valvular regurgitation and verifying proper inflow cannula placement. Adequate ventricular decompression can be confirmed. In the case of axial flow devices, pump speed can be adjusted with TEE guidance to ensure adequate ventricular decompression while avoiding collapse of the LV and septal shift.

Right ventricular failure

Approximately 20–30% of patients undergoing left VAD placement will suffer from postoperative right heart dysfunction [12, 33, 34]. A recent series examined the incidence of right heart failure in patients with chronic congestive heart failure undergoing LVAD implantation [35]. In 108 patients, right-sided circulatory failure was seen in 42 patients (38.9%), with 14 patients requiring implantation of an RVAD. Postoperative right ventricular failure has a significant effect on clinical outcomes, leading to increased ICU length of stay, increased 30-day mortality following LVAD implantation, and a lower bridge to transplantation rate [34–36].

Right-sided circulatory failure can result from abnormalities both in the right ventricle as well as the pulmonary vascular bed. Perioperative factors include myocardial stunning, ischemia, infarction, air embolism, and arrhythmias. Changes in ventricular interdependence and septal shifting secondary

to mechanical unloading of the left ventricle can also contribute to impaired right-sided function [37]. In addition, preexisting right ventricular dysfunction may be unmasked secondary to the augmented preload presented to the right side following LVAD implantation [34].

Predicting which patients will manifest right-sided failure can be difficult. Several authors have described preoperative risk factors for the development of RV failure. Ochiai *et al.*, in an analysis of 245 patients undergoing LVAD placement, found preoperative circulatory support, female gender, and non-ischemic etiology for heart failure as risks for postoperative RV failure requiring RVAD placement. In addition, hemodynamic parameters associated with RVAD use were low mean and diastolic pulmonary arterial pressures, low right ventricular stroke work (RVSW), and low RVSW index (RVSWI), most likely identifying patients with impaired RV contractility. Elevated pulmonary vascular resistance and pulmonary arterial pressures were not identified as risk factors [38]. Similar findings have been previously reported [39].

More recently, the right ventricular failure risk score (RVFRS), developed by Matthews and colleagues at the University of Michigan, provides a way of stratifying risk of postoperative RV failure [15]. Utilizing information from a prospectively collected database, 197 LVAD implants were examined. Right ventricular dysfunction was found in 35% of cases. Independent predictors of RV failure were the preoperative requirement of a vasopressor, aspartate aminotransferase (AST) $\geq$ 80 IU/L, bilirubin $\geq$ 2.0 mg/dL, and serum creatinine $\geq$ 2.3 mg/dL. Each clinical predictor was assigned a point score, and a cumulative risk score was then derived. Survival to transplantation and overall survival declined as the RVFRS increased, again confirming the negative impact of postoperative RV failure on outcomes following LVAD implantation. Fitzpatrick and colleagues recently analyzed a series of 266 LVAD recipients. In this study, predictors of the need for biventricular mechanical support were cardiac index, RV stroke work index, severe preoperative RV dysfunction, preoperative creatinine, previous cardiac surgery, and systolic blood pressure [40].

Several factors contribute to perioperative right ventricular dysfunction including intrinsic abnormalities of the ventricular myocardium and impaired contractility, elevated pulmonary vascular resistance, and the effects of ventricular interdependence and septal shift. Preoperatively, every effort should be made to optimize right ventricular function. This includes correction of volume status with diuresis, and in many cases, inotropic support of the right ventricle. In selected patients, preoperative use of intra-aortic balloon pump counterpulsation may be of benefit, particularly in those that have potentially reversible hepatic and renal dysfunction. A history of obstructive sleep apnea should be sought, especially in obese patients, and treated to alleviate hypercarbic-induced pulmonary hypertension. In addition, the use of sildenafil preoperatively in patients with pulmonary hypertension has been shown to be a useful adjunct in reducing pulmonary vascular resistance prior to LVAD implantation [41].

During implantation, attempts to minimize cardiopulmonary bypass time can alleviate the deleterious effects of extracorporeal circulation on RV function [42]. When possible, outflow graft anastomosis to the aorta can be performed off-pump. For placement of the LV inflow cannula, normothermic bypass is used without cardioplegic arrest. Depending on the patient's coronary anatomy, rare cases of concomitant bypass grafting to the right coronary system at the time of LVAD insertion have been described to avoid perioperative right-sided ischemia or infarction. Meticulous de-airing when weaning from bypass support is important to prevent air embolization to the coronary arteries. As will be discussed in a separate section, patients undergoing LVAD placement are often coagulopathic and require blood component transfusion. Meticulous surgical technique must be used to avoid excessive bleeding from anastomotic sites. Blood transfusions must be administered judiciously to avoid excessive volume overload as well as to minimize the adverse effects on pulmonary vascular resistance [42].

Right-sided dysfunction can present over a spectrum of severity. Clinically, the onset of RV failure can be sudden and may occur at the onset of LVAD device initiation or can be more insidious with a persistent inotropic requirement postoperatively. Right-sided failure results in elevated central venous pressure and impaired filling of the left side, with low device flows and ultimately compromised end-organ perfusion. Early recognition and aggressive treatment are critical for successful management. Intraoperatively, aggressive inotropic support of the RV with phosphodiesterase inhibitors, as well as epinephrine or dobutamine, is initiated prior to weaning from bypass and continued in the postoperative period. Hyperventilation, as well as the use of selective pulmonary vasodilators such as inhaled nitric oxide or prostacyclin, is routinely employed. Atrial and ventricular arrhythmias must be treated, and if necessary, atrioventricular sequential pacing is utilized to maximize RV performance. If these measures are inadequate, then early consideration must be given to implantation of an RVAD. Improvements in medical management of RV failure have resulted in a decreased incidence of RVAD implantation [43, 44]. A recent report comparing the occurrence of right heart dysfunction following implantation of pulsatile versus axial flow devices found a similar incidence postoperatively but a trend toward decreasing need for RVAD placement in the axial flow group [45]. When RVAD support is necessary, improved clinical results have been demonstrated by early implantation within 24 hours [36].

Infection

Infection remains a significant source of morbidity and mortality in patients receiving mechanical circulatory support. In the REMATCH trial, the leading cause of death in patients receiving devices was sepsis, accounting for 20 of 52 deaths in this group [7]. A subsequent analysis focusing on infection during the REMATCH trial showed that freedom from sepsis in patients with LVADs was 58% at 1 year and 48% at 2 years. The peak hazard for sepsis occurred

early within 30 days from implantation [46]. In the recent Heartmate II trial, device-related infection was seen in 14% of patients. All device infections involved the percutaneous lead, with no infections seen in the pump pocket. Localized infection unrelated to device placement was seen in 28% of recipients [21].

Infections in LVAD patients can affect different components of the device and can vary in severity. These include infections at the driveline exit site, device pocket infections, device endocarditis, and bloodstream infection [47, 48]. Bloodstream infections have a significant correlation with mortality in patients undergoing device placement, with the highest risk of death seen in those developing fungemia [49]. A wide range of infection rates have been reported in the literature, partly due to varying definitions of device infections [12, 50]. Overall infection rates in patients receiving devices at all sites have been approximately 50% [46, 48]. Up to 25% of deaths in LVAD patients are due to systemic sepsis, which occurs in 11–26% of patients [51, 52]. Bacteria that are able to form a biofilm are common pathogens, including Staphylococcus, Pseudomonas, Enterococcus, and Candida [51, 53]. While some patients can be treated nonoperatively with antibiotic suppressive therapy, others may need surgical drainage of abscesses or fluid collections, debridement, or device exchange. In some cases, the only therapeutic option is device removal and transplantation. Fortunately, device-related infections do not seem to have an adverse impact on transplant outcomes [54].

Several preoperative factors increase the risk of developing infectious complications after device placement. Patients suffering from end-stage heart failure are often chronically debilitated and malnourished. Comorbid conditions such as diabetes with poor glucose management, chronic renal insufficiency and azotemia, peripheral vascular disease, chronic pulmonary disease, and advanced age all increase risk. In addition, many patients undergoing LVAD implantation have been hospitalized and may harbor nosocomial infections at remote sites such as pneumonia, urinary tract infections, or blood-borne infections secondary to chronically indwelling vascular lines. The preoperative use of immunosuppressive medications as well as immunological derangement associated with activation of T-cell death seen after device implantation also contribute to the risk of both early and late infection [55].

Preoperatively, every effort should be made to correct reversible medical factors that can predispose to infectious complications. Infections at remote sites such as the lungs, urine, oropharynx (dental caries), abdomen, or blood must be identified and controlled prior to operation. Whenever possible, indwelling central lines and intra-aortic balloon pumps should be either removed or exchanged prior to or at the time of LVAD implant. One of the most critical factors contributing to the risk of infection is the patient's nutritional status. Along with this is the importance of rigorous glycemic control perioperatively, particularly in those with diabetes. VAD patients are often malnourished and cachectic due to problems of anorexia, impaired gastrointestinal function due to low cardiac output, and a chronic catabolic

state secondary to the neurohumoral changes associated with heart failure. As has been described, an interdisciplinary approach to nutritional assessment and management is highly effective [56]. Nutritional supplementation should in many cases begin preoperatively with continuation of enteral feeding in the early postoperative period.

Guidelines regarding the use of perioperative antibiotics have been previously reported [48]. In general, prophylaxis is directed toward common pathogens, such as staphylococci, as well providing Gram-negative and antifungal coverage. Cooperation with infectious disease specialists is helpful in custom tailoring regimens based on sensitivities within a given institution. Most antibiotics are continued for 48 hours postoperatively. Standard protocols regarding topical and nasal decontamination with chlorhexidene showering and antimicrobial nasal ointments are also important adjuncts to patient preparation.

The intraoperative conduct of the procedure remains the most crucial phase with respect to preventing device-related infections. Standard sterile technique in regard to patient prepping and draping, staff preparation, and operating room environment must be followed meticulously. Attention to sterile procedure must be followed both operatively and preoperatively during placement of central venous and arterial catheters. Device opening and preparation are performed close to the time of implantation. During implantation, the LVAD is usually wrapped and handled in antibiotic soaked sponges. Creation of the driveline tract should allow for adequate percutaneous tunnel length to maximize tissue ingrowth. The driveline exit site is usually positioned in the right upper quadrant below the costal margin to maximize patient comfort and promote tissue incorporation. Driveline immobilization at the exit site is critically important to promote healing and prevent infection, and this should be done prior to leaving the operating room. Adequate hemostasis and drainage of the mediastinum and LVAD pocket are important for preventing postoperative hematoma formation, which can serve as a culture medium for bacterial growth. Finally, secure fascial wound closure must be achieved, particularly in the region of the device pocket, without excessive tension. In some cases, prosthetic mesh may be used to achieve a tension-free closure.

Many of the previously mentioned management strategies must continue into the postoperative period. Prophylactic antibiotic administration should usually not extend beyond 48 hours postoperatively. An attempt is made to remove central venous lines when they are no longer needed. If prolonged intravenous therapy is required, then consideration should be given to placement of a percutaneous placed central line or tunneled catheter. Nutritional support, preferably in the form of enteral feeding, is initiated early and continued until nutritional parameters have normalized. Finally, maintenance of driveline immobilization and local dressing care is of utmost importance. The exit site remains a portal of entry for bacterial proliferation. Patient education is of primary importance and should be initiated early in the recovery process.

Prior to discharge, health care providers should observe patients performing dressing changes in order to verify that the patients understand and utilize proper sterile technique and wound care.

The treatment of infection remains a challenge in device recipients. Any patient with unexplained fever or leukocytosis should be presumed to have a device-related infection until proven otherwise. Infections can involve the driveline exit site, the ascending driveline, and pump pocket, or intravascular components of the device and bloodstream. Infection at remote sites should also be sought out. Imaging studies such as ultrasound, computed tomography, or gallium scanning can be useful in identifying deep space abscesses or collections. Depending on the severity of infection, signs can range from mild cellulitis to purulent drainage from the exit site with tenderness and signs of sepsis (Figure 22.3). At the first suspicion of infection, local wound and blood cultures should be taken and antimicrobial therapy tailored accordingly. Chinn and colleagues have categorized driveline infections as mild, moderate, and severe [48]. While mild and moderate infections can often be managed with local wound care and suppressive antibiotics, severe infections may require open surgical drainage and driveline revision. Late presenting driveline infections also continue to be a source of morbidity [57]. Device pocket infections usually cause pain over the pump pocket and along the driveline and typically result in drainage from the driveline tract. Any abscesses within the pocket must be drained either percutaneously or with open surgical drainage. Bloodstream device infections, in some cases, can be managed with suppressive antibiotics. However, often they are refractory to antibiotic therapy and can be managed definitively only by either device

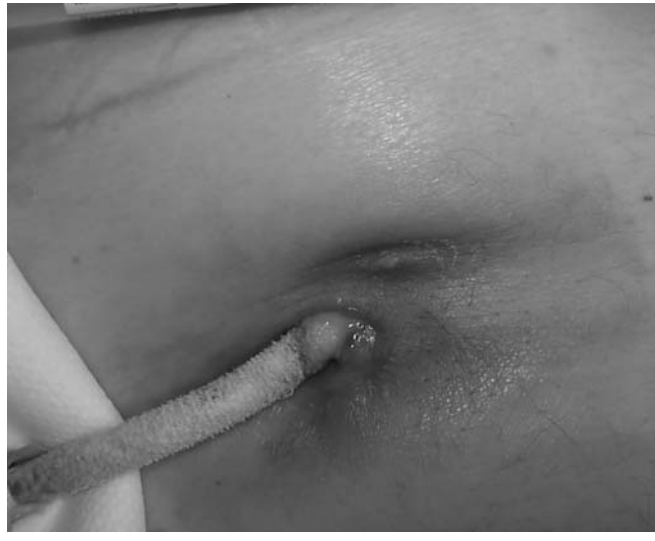

Figure 22.3 Driveline exit site infection.

removal and transplantation or device exchange in patients not eligible for transplant.

Hematologic derangement

Mediastinal bleeding following LVAD implantation is relatively common, occurring in some series in as many as 48% of patients [12, 50]. In the recent continuous-flow LVAD trial, bleeding was the most common adverse event, seen primarily in the early postoperative period (0–30 days) [21]. Reoperation was required in 31% of patients. This is likely a reflection of the need for early postoperative anticoagulation with heparin and warfarin when using continuous-flow devices. Predisposing factors include passive hepatic congestion and impaired production of coagulation factors, compromised nutritional status, the use of preoperative anticoagulation, extensive surgical dissection, reoperative procedures, and prolonged cardiopulmonary bypass. In addition, LVAD patients develop coagulopathy secondary to interactions between circulating blood elements and the artificial device surfaces [58]. The development of acquired von Willebrand disease following device placement has also been described [59]. Preoperatively, every effort is made to normalize the coagulation profile. Diuresis with relief of hepatic congestion, administration of fresh frozen plasma, and vitamin K supplementation can all be utilized. If possible, anticoagulants such as warfarin and clopidogrel should be discontinued at least 5 days prior to LVAD implant.

At the time of operation, meticulous surgical technique is used when constructing the inflow and outflow conduits. Fresh frozen plasma can be used to prime the cardiopulmonary bypass pump, and attention should be focused on minimizing bypass times and ensuring adequate rewarming prior to separation from bypass. Hemostasis can be achieved with judicious blood component transfusion therapy in the form of platelets, fresh frozen plasma, and cryoprecipitate. Recombinant factor VII has also been used for refractory coagulopathic bleeding, but it should be used with caution in device patients due to its tendency for thrombosis. Topical hemostatic agents can also be a useful adjunct. In the past, the serine protease inhibitor aprotinin has been shown to be of benefit in patients undergoing device implantation. The use of aprotinin has been shown to decrease blood loss, the incidence of RVAD implantation, and perioperative mortality in patients undergoing LVAD placement [60]. However, recent concerns regarding the effects of aprotinin use on renal function, thromboembolic events, and late mortality in cardiac surgery have relegated its use to historical interest [61, 62]. Aminocaproic acid is used commonly as an antifibrinolytic agent.

There should be a low threshold for reexploration in the setting of persistent postoperative bleeding. Cardiac tamponade results in impaired right ventricular function, with subsequent decreased LVAD filling and reduced pump flows. Early reoperation also allows for evacuation of mediastinal and pump pocket hematoma that can serve as a nidus for infection. For devices requiring anticoagulation, there has been a trend in recent years at some centers

to avoid the use of perioperative heparin and simply to begin oral warfarin on the second or third postoperative day. Due to the requirement of systemic anticoagulation for many devices, as well as the routine use of aspirin as an anti-inflammatory agent, late bleeding and tamponade can occur as well. A high index of suspicion must be maintained in patients with decreased pump flow rates unresponsive to fluid challenge, elevated filling pressures, respiratory distress, or signs of end-organ dysfunction [63].

Thromboembolism

Thromboembolic events can lead to devastating neurologic and end-organ injury and remain a significant concern in patients undergoing mechanical device placement. Approximately one-third of patients having an LVAD will suffer from such an event [64]. In the REMATCH trial, the rate of neurologic events was 4.35 times higher than in the medically treated group, with 47% of such events being transient [7]. Difficulty in accurately comparing the incidence of thromboembolism among different devices is partly due to inconsistent definitions, as described by Pasque and Rogers [65]. The Heartmate XVE, with its sintered titanium and textured polyurethane internal surfaces, has a relatively low incidence of thromboembolic events without the need for systemic anticoagulation with heparin or warfarin. Second- and third-generation rotary pumps usually require systemic anticoagulation to maintain an INR between 2.0 and 3.0. In addition, depending on the system used, many patients are maintained on antiplatelet therapy with aspirin, dipyridamole, or clopidogrel. Pump thrombosis remains a potential mode of device failure with continuous-flow devices, and it can lead to thromboembolic complications. In the recent Heartmate II trial, the incidence of stroke was 8% (6% ischemic, 2% hemorrhagic), and the incidence of transient ischemic attacks was 4% [21]. Vigilant control of anticoagulation parameters is necessary to balance the risk of thrombus formation with the threat of late mediastinal bleeding.

Any history of a prior thromboembolic event such as stroke, transient ischemic attack, or deep venous thrombosis should prompt a thorough workup for a hypercoagulable disorder. Preoperative echocardiography should be used to identify any preexisting intracardiac thrombus, particularly in the left atrium or left ventricle, as these structures are frequently enlarged, and subject to thrombus formation, in chronic heart failure. At the time of operation, careful direct inspection should be made of the left ventricular cavity after coring. If thrombus can be identified, then it should be removed if it can be done so safely. In some cases, apical thrombus can be very well incorporated and organized and intimately associated with myocardial trabeculations, making fragmented removal hazardous. In such cases, it can be left in situ. Intraoperatively, care must also be taken to avoid air embolization. Adequate ventricular filling is mandatory prior to device actuation. In addition, with axial flow devices, speed is gradually increased with continuous echocardiography to avoid the creation of negative suction within the ventricular cavity. Complete evacuation of intracavitary air is confirmed by intraoperative TEE prior to

separation from bypass. Postoperatively, a thromboembolic event is usually the result of clot formation either within a cardiac chamber or within the pump itself. Echocardiography is useful for diagnosis. Treatment usually involves increasing the level of anticoagulation and may necessitate pump exchange.

Immunologic effects and allosensitization

The interaction between prosthetic device surfaces and circulating blood elements has systemic immunologic effects in patients undergoing device implantation. Itescu and coworkers have described the specific cellular changes that occur [66]. A number of alterations are seen in T-cell function. These include aberrant T-cell activation, heightened T-cell proliferation, increased apoptotic cell death, and simultaneous defects in T-cell proliferation in response to T-cell receptor activation. In addition, T cells in LVAD patients demonstrate increased susceptibility to activation-induced cell death. Another aspect of immunologic disturbance that is seen is B-cell hyperreactivity. Alterations in circulating cytokines and cellular milieu are postulated to be responsible for polyclonal B-cell activation. Patients undergoing LVAD placement have a higher frequency of circulating antiphospholipid and anti-HLA antibodies [55, 66].

The overall clinical effect of these changes is twofold. First, patients demonstrate progressive defects in cellular immunity, with a resultant increased risk of infection. Second, B-cell hyperreactivity ultimately leads to allosensitization to HLA antigens. In an analysis of a series of 105 patients at Columbia University undergoing cardiac transplantation after being bridged with an LVAD, 66% were sensitized prior to transplant, as opposed to only 6% of nonbridged patients [67]. Untreated allosensitization is associated with prolonged pretransplant waiting times, as well as an increased risk of acute rejection [67]. When sensitization develops, immunomodulation with intravenous immunoglobulin therapy in conjunction with cyclophosphamide has proven to be effective in reducing alloreactivity and reducing the risk of acute rejection [66, 67]. Plasmapheresis, with serial monitoring of panel reactive antibodies, and prospective crossmatching are other modalities. As device design continues to change, so, too, will the immunologic effects of LVAD placement. Studies are presently in progress to characterize the effects of continuous-flow pumps on allosensitization.

Conclusions

Ventricular assist devices represent an important advancement in the treatment of patients suffering from heart failure. Newer generation devices are smaller in size with fewer moving parts, potentially offering the advantages of implantation with less surgical trauma and enhanced durability. Efforts toward the development of smaller devices, transcutaneous energy sources, and minimally invasive implantation techniques are aimed at reducing

complications associated with current device therapy. This will likely lead to an increase in the widespread use of LVADs earlier in the progression of heart failure as well as increasing the use of devices for long-term destination therapy in patients not eligible for cardiac transplantation.

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CHAPTER 23

Aortic and Great Vessel Operations

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Present day cardiac and cardiovascular surgeons have experienced significant progress toward reducing complications during aortic and great vessel surgery. This can be attributed to enhanced preoperative imaging modalities, advances in graft materials and biologic glues, improved anesthetic techniques and strategies for cerebral and spinal cord protection, and the emergence of endovascular technology. While open aortic and great vessel procedures continue to be associated with a wide range of complications and a small but not insignificant mortality rate, endovascular procedures have been associated with a new set of complications. As technology evolves and new therapies are introduced, we must be creative in the prevention and management of previously unrecognized complications.

Aortic and great vessel operations are complex procedures that often require extensive surgical incisions and anatomic exposures, long operating times, transient end-organ ischemia, and occasionally the need for extracorporeal circulation and hypothermic circulatory arrest. In addition, the violation of major (and sometimes multiple) body cavities in association with blood loss, blood pressure fluctuations, and fluid shifts can significantly increase the risk of specific postoperative complications for patients who often enter the operating room with significant preexisting cardiopulmonary, renal, or cerebral vascular disease. As challenging as these patients may be to care for, intraoperative complications are usually not the greatest concern. Present day imaging and image reconstruction software usually allow for detailed preoperative anatomic surgical planning, and as a result unmanageable intraoperative technical complications should be exceedingly rare. Operations on the aorta and great vessels are indicated for a number of reasons, but aneurysmal and occlusive disease are the most common. Close communication between the surgeon and the entire operating team, particularly the anesthesiologist and perfusionist, is paramount to a successful surgical outcome.

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Neurologic complications

Neurologic complications that occur during aortic surgery can range from transient dysfunction such as postoperative confusion or agitation to permanent damage with the associated lifelong physical and mental disabilities. Perfusion strategies developed to combat these morbidities during aortic operations include profound hypothermic circulatory arrest (PHCA), antegrade cerebral perfusion (ACP), and retrograde cerebral perfusion (RCP). PHCA was pioneered in London by Charles Drew in 1959 [1]. Since then, it has become a common strategy for cerebral protection in thoracic aortic repairs. Dr Elefteriades' group recently evaluated their experience of PHCA in 394 patients over a 10-year period [2]. With a mean circulatory arrest time of 31 minutes and only PHCA as a means of cerebral protection, their overall stroke rate was 4.8%. The stroke rate among the elective ascending and aortic arch patients was only 2.3%. Overall, approximately two-thirds of the strokes were attributed to embolic phenomena and one-third was attributed to hypoperfusion. In France, Dr Bachet's group has used an ACP strategy they initially developed in 1986 [3]. This technique involves selective antegrade perfusion of the cerebral vessels with 6–12°C blood and moderate systemic hypothermia (25–28°C) with brief circulatory arrest as needed, all while avoiding profound hypothermia and the associated longer cardiopulmonary bypass times required for cooling and rewarming. Over a 14-year period, this group evaluated 171 patients in whom this strategy was used and found an overall neurologic complication rate of 12.8% [4]. Advantages of this technique are that it does not limit the surgeon in terms of time to repair the aortic arch and great vessels, and it avoids the use of deep hypothermia and minimizes the associated risks of deep hypothermic perfusion and total circulatory arrest.

A third technique developed for cerebral protection involves RCP. Initially described to treat massive air embolisms during cardiopulmonary bypass, this technique involves selective cannulation of the superior vena cava and retrograde flow to maintain a predetermined central venous pressure [5]. Ehrlich *et al.* retrospectively evaluated their experience with this technique in 1999 [6]. A total of 109 patients were evaluated with 55 patients undergoing hypothermic circulatory arrest alone compared to 54 patients with hypothermic circulatory arrest with RCP. Circulatory arrest times were 30 and 33 minutes, respectively, and the stroke rate significantly favored RCP as a protective strategy (27% vs. 9%; $p = 0.01$). Further, on multivariate analysis, a lack of RCP was an independent predictor for a stroke. It is interesting that in this study, there was no difference in temporary neurologic dysfunction among the groups (17% vs. 18%; $p = 0.9$). Our method of cerebral protection is PHCA combined with the use of RCP. We ensure the central venous pressure stays less than 35–40 mm Hg during RCP. We do not routinely pretreat patients with barbiturates or steroids, but we do use cerebral oximetry, flood the field with carbon dioxide, maintain strict glycemic control during the operation, and pack the head in

ice. Although the data for these adjuvant techniques is not robust, we believe they do make some impact in protecting the brain during circulatory arrest.

Embolization is an unfortunate phenomenon that continues to challenge the field of aortic surgery and contributes significantly to the overall morbidity and mortality. To evaluate the contribution of atherosclerotic aortic disease to the risk of having a postoperative stroke, Jan van der Linden *et al.* prospectively used epiaortic ultrasound to assess the presence of calcification and the location of atheroma in 921 consecutive patients undergoing cardiac surgery [7]. In patients without atherosclerotic disease of the ascending aorta, the incidence of postoperative stroke was 1.8% compared with an 8.7% incidence in patients with atherosclerosis ($p < 0.0001$). Interestingly, atherosclerotic disease involving the middle-lateral segment of the ascending aorta was an independent predictor for having a postoperative stroke. Because of the increased incidence of emboli in patients with atherosclerotic plaques and diseased aortas, many strategies to avoid certain areas of these aortas have been attempted. Strategies such as routine epiaortic ultrasound and preoperative noncontrasted CT scans have been utilized to help reduce the incidence of emboli. Das *et al.* selected 8 studies out of 179 to answer the question "Does epi-aortic ultrasound reduce the incidence of postoperative stroke during cardiac surgery?" [8]. Five of the eight studies showed a reduction of the stroke rate as a result of modifying the surgical technique from the results of the epiaortic ultrasound exam. The authors concluded that epiaortic ultrasound scanning is more accurate for detecting aortic atheroma than manual palpation.

A study by Lee *et al.* evaluated preoperative noncontrasted CT scanning versus epiaortic ultrasound scanning, comparing a group of 230 consecutive patients who underwent selective epiaortic ultrasound to a group of 273 consecutive patients who received a preoperative noncontrasted CT scan of the chest [9]. Of the 230 patients in the selective epiaortic ultrasound group, 7 patients underwent an ultrasound study and a deviation from the operative plan was noted in one patient. Of the 273 patients undergoing CT scanning, the scan identified 20 patients with significant aortic calcifications and resulted in a deviation from the operative plan in 19 patients. The overall stroke rate for the two groups was 3.04% in the epiaortic ultrasound group and 0.73% ($p = 0.05$) in the CT scan group. The authors concluded that preoperative CT scanning of the chest is superior to epiaortic ultrasound for preventing stroke in high-risk patients. Factors indicating those at high risk included a history of stroke or transient ischemic attack, peripheral vascular disease, end-stage renal disease, age greater than 70 years old, and aortic calcification noted on cardiac catheterization.

Protecting the spinal cord from ischemic injury during aortic surgery continues to be a major challenge for the aortic surgeon. Four types of thoracoabdominal aortic aneurysms have been described by Dr Crawford, and because of the length and location of aorta involved, Crawford type II aneurysms tend to have the highest risk for spinal cord ischemia. For type II thoracoabdominal

aortic aneurysms, the incidence of paraplegia ranges from 7% to 32% [10]. Many strategies have been developed to reduce the risk of spinal cord injury during thoracic aortic surgery. Left atrial to femoral artery bypass, intercostal artery reimplantation, cerebrospinal fluid cooling, cerebrospinal fluid drainage, intraoperative neuromonitoring, and postoperative blood pressure management have helped to decrease the rate of paraplegia and paraparesis following thoracic aortic surgery [11–13]. Safi *et al.* demonstrated a reduced risk of neurologic injury following type II thoracoabdominal aneurysm repair using cerebrospinal fluid drainage and distal aortic perfusion [11]. In this study, the additive effect of these modalities resulted in an increase in spinal cord perfusion pressure during the aortic cross-clamp period. The control group consisted of 42 patients who underwent thoracoabdominal aneurysm repair with only a cross-clamp and no additional modality to aid in spinal cord perfusion. For type II thoracoabdominal aneurysm repairs, the authors showed a reduction in spinal cord related neurologic complications from 19% in the control group (8 of 42 patients) to 9% in the experimental group (8 of 94 patients) ($p = 0.014$).

Another strategy used to help assess and limit spinal cord ischemia during thoracic aortic operations is the measurement of motor-evoked potentials (MEPs). When MEPs indicate ischemia, treatment options include increasing aortic perfusion pressure if using left heart bypass, increasing mean arterial pressure with vasopressor agents or volume, identifying critical intercostals or lumbar arteries, and reimplantation of the involved region with the goal being to revascularize any significant back-bleeding vessels. To evaluate the impact of MEP monitoring in thoracoabdominal aortic operations, Jacobs *et al.* devised a surgical protocol that included cerebrospinal fluid drainage, moderate hypothermia, left heart bypass with selective organ perfusion, and spinal cord ischemia assessment via monitoring of MEPs to 112 consecutive patients undergoing thoracoabdominal aortic operations [14]. They were able to monitor MEPs in all patients and by maintaining a mean distal aortic pressure of 60 mm Hg, 82% of the patients had adequate MEPs. In 19 patients, MEPs significantly decreased during aortic cross-clamping but returned to baseline once aortic flow was reestablished. Unfortunately in three patients, MEPs did not return after reestablishing aortic flow and this correlated with a neurologic deficit postoperatively. This study demonstrated that monitoring MEPs is a very reliable and accurate method to assess spinal cord ischemia and allows the potential to act upon ischemic events in hopes of eliminating neurologic injury during such procedures. Despite the overall success with this technique though, a small but not insignificant number of patients did develop paraplegia.

An additional technique described to help decrease the risk of spinal cord injury during thoracic aortic operations is epidural cooling. In 1993, Cambria *et al.* described a technique in which they infused normal saline at 4°C into the epidural space using an epidural catheter positioned at the T11–T12 vertebral body level [13]. A second catheter was placed intrathecally at the L3–L4 level

to monitor both temperature and pressure of cerebrospinal fluid. In 2000, this group published their experience with this technique in 170 patients undergoing repair of thoracic aortic or thoracoabdominal aneurysms [15]. They used a clamp and sew technique with selective reimplantation of critical intercostal or lumbar vessels in the T9–L1 region. The overall operative mortality was 9.5% with postoperative cardiac complications and renal failure being independent predictors of death. Spinal cord injury occurred in 7% of the patients overall versus a predicted incidence of 18.5%. Of the patients with spinal cord injury, half were minor with good functional recovery and only 3 (2%) had long-term deficits. Multivariate analysis identified type I or II thoracoabdominal aneurysms, emergent operation, oversewn T9–L2 intercostal vessels, and postoperative renal failure as independent predictors of spinal cord injury.

At the University of Virginia, we prefer the use of RCP during hypothermic circulatory arrest for straightforward ascending aorta and aortic arch operations requiring less than 30 minutes of cerebral ischemia time. For complex aortic arch and great vessel operations, we are fully prepared to utilize antegrade cerebral perfusion through either the right axillary artery or the origin of the innominate or left carotid arteries. The use of both techniques in combination has also been helpful depending on the anatomy and complexity of the condition being treated. For extensive descending thoracic and thoracoabdominal aortic operations, we routinely utilize left heart bypass with passive systemic cooling in conjunction with cerebrospinal fluid drainage. We maintain CSF drainage for the first 48 hours after surgery in conjunction with optimal systemic blood pressure. We strive to maintain the CSF pressure less than 10 cm H_2O and a mean systemic arterial blood pressure of greater than 85 mm Hg. With present day small diameter cannulas that provide excellent flow characteristics in conjunction with axial flow pumps and heparinized circuits, complications related to the bypass circuit and excessive anticoagulation are minimal.

Cardiac complications

In general, patients with aortic pathology are at an increased risk of heart disease. This association reflects the high prevalence of coronary atherosclerosis in this group of patients. In a study in which patients with abdominal aortic aneurysms underwent cardiac catheterization for risk stratification, 31% had severe coronary artery disease [16]. Thus, a complete evaluation is required for every patient preoperatively to determine which patients are at increased risk and deserve further evaluation. How extensively one should evaluate a patient who is to undergo major aortic surgery is not clear. Routine, cardiac catheterization will result in a small number of patients that will undergo either percutaneous coronary intervention or surgical coronary revascularization with a less than ideal outcome resulting from the coronary intervention. Functional studies to identify silent coronary ischemia are available, and the specific study chosen varies from institution to institution.

A number of risk indices have been developed in the past to determine who warrants further evaluation. The Revised Cardiac Risk Index by Lee *et al.* identified six parameters that were independent predictors of major cardiac complications from a study of over 4000 patients undergoing major nonemergent noncardiac procedures [17]. These parameters include high-risk type surgery, history of ischemic heart disease, history of congestive heart failure, history of cerebrovascular disease, preoperative treatment with insulin, and preoperative serum creatinine greater than 2.0 mg/dL. Depending on the number of parameters present preoperatively, 0, 1, 2, 3, or greater, the rate of major cardiac complications in the derivation cohort was 0.5%, 1.3%, 4%, and 9%, respectively. In the validation cohort from the study, a similar percentage of cardiac complications were found: 0.4%, 0.9%, 7%, and 11%, respectively. This study provides us the opportunity to identify high-risk patients who may benefit from further cardiac evaluation.

After identifying those patients with an increased risk for perioperative cardiac events, the next step is to decide which study to utilize to further characterize and quantify their cardiac risk. Several noninvasive studies are available to evaluate cardiac risk including: exercise electrocardiography, dipyridamole myocardial perfusion scintigraphy, and dobutamine stress echocardiography. Although all of these tests do a reasonable job in providing data to stratify cardiac risk, in a recent meta-analysis dobutamine stress echocardiography performed best [18]. Recently, newer techniques such as cardiac magnetic resonance imaging and cardiac computed tomography have been developed to further predict patients' cardiac risk [19]. The overall utility of these tests for preoperative evaluation remains to be determined. While exercise treadmill stress testing is often regarded as a sensitive test to rule out significant coronary disease, few patients facing major aortic or great vessel surgery are able to undergo this sort of evaluation. The functional test chosen depends on the local expertise of the institution and those involved in the evaluation of the study. In the end, the operating surgeon needs to be involved in the decision making process as to which, if any, functional test to order and how to act on the results of that study.

Beta-blockers, statins, and alpha-2 adrenergic blockers have shown some promise in decreasing perioperative cardiac risk. Bisoprolol was studied in a randomized fashion in 112 patients undergoing noncardiac vascular surgery with one or more cardiac risk factors and a positive dobutamine stress echocardiographic study. This study showed a significantly lower end point of cardiac death and myocardial infarction within 30 days after surgery in patients randomly assigned to bisoprolol (3.4% bisoprolol group vs. 34% in the control group ($p < 0.001$)) [20]. Statins also are believed to have beneficial effects on cardiac morbidity in the perioperative setting. Durazzo *et al.* evaluated 20 mg atorvastatin in a randomized placebo-controlled trial with 100 patients for 45 days irrespective of their serum cholesterol level [21]. Vascular surgical procedures were then performed at about 30 days from the start of the drug, and 6-month end points included death from cardiac cause, nonfatal

myocardial infarction, unstable angina, and stroke. Patients taking atorvastatin had a significantly lower rate of cardiac events at 6 months ($p = 0.018$). Although the data on alpha-2 adrenergic blockers are not as clear, a meta-analysis in 2003 of 23 trials by Wijeysundera *et al*. showed a reduced mortality (RR = 0.47, $p = 0.02$) and myocardial infarction rate (RR = 0.66, $p = 0.02$) following vascular surgery [22]. This group concluded, however, that larger randomized studies were necessary to fully evaluate these findings.

Many patients requiring aortic and great vessel surgery have undergone recent or remote coronary intervention with either bare metal or drug eluting coronary stents. The use of Plavix in these patients is often critical for the patency of their stents, yet significantly increases the risk of perioperative bleeding. Patients with bare metal stents experience an early risk of stent thrombosis if Plavix is withheld, but only within the first 6 weeks after stent placement. For patients receiving bare metal coronary stents, surgery should be delayed 6 weeks if possible, at which time Plavix can safely be held for at least 3–5 days prior to surgery. After the initial 6-week period, treatment with aspirin alone is sufficient. Patients with drug eluting stents have a small but not insignificant lifetime risk of stent thrombosis upon discontinuation of Plavix. As a result, patients with drug eluting coronary stents who require major aortic or great vessel surgery should have their Plavix discontinued for only 3–5 days prior to surgery, and then have Plavix restarted within 48 hours of surgery to minimize the chance of acute stent thrombosis.

Pulmonary complications

The ability to predict a patient's postoperative risk of pulmonary complications inherently seems simple. With an adequate history, and basic studies including spirometry, an arterial blood gas, and a chest x-ray, one should be able to stratify a patient's risk. Postoperative pulmonary complications significantly increase the mortality rate for patients undergoing surgery [23, 24]. These complications include pneumonia, atelectasis, diaphragm dysfunction, prolonged mechanical ventilation, bronchospasm, and ventilation perfusion mismatch. Unfortunately, the ability to predict pulmonary complications is not as straightforward and precise for a number of reasons. For one, studies vary on the definition of postoperative respiratory failure. In two separate studies evaluating postoperative respiratory failure, the length of postoperative days on the ventilator equating to respiratory failure varied between 2 and 5 days [23, 25]. Second, anesthesia alone can increase the risk of respiratory failure. The mechanism is believed to be multifactorial. Factors such as decreasing the mucociliary clearance of the tracheobronchial tree, decreasing the number of alveolar macrophages and increasing the permeability of the alveolar capillary membrane can contribute to pulmonary complications [26–28]. Also, general anesthesia reduces the FRC (functional residual capacity) leading to ventilation perfusion mismatch, further contributing to postoperative complications [29].

Table 23.1 Respiratory failure risk index.

Preoperative predictor	*Point value*
Type of surgery	
Abdominal aortic aneurysm	27
Thoracic	21
Neurosurgery, upper abdominal, or peripheral vascular	14
Neck	11
Emergency surgery	11
Albumin (<30 g/L)	9
Blood urea nitrogen (>30 mg/dL)	8
Partially or fully dependent functional status	7
History of chronic obstructive pulmonary disease	6
Age (years)	
≥70	6
60–69	4

Source: From Ref. [24]. Permission request submitted to Lippincott Williams and Wilkins.

To help better predict postoperative respiratory failure, Arozullah *et al.* used a prospective cohort study and evaluated cases from 44 Veterans Affairs Medical Centers to develop a respiratory failure risk index [24]. A total of 81719 cases were used from various surgical procedures including upper abdominal surgery, neurosurgery, abdominal aortic aneurysms, peripheral vascular surgery and orthopedic surgery to develop the model (phase I). The model was then validated from 132 Veterans Affairs Medical Centers using 99 390 cases (phase II). The respiratory risk failure index was based on a point system using the following categories: type of surgery, emergency surgery, albumin, blood urea nitrogen, functional status, history of chronic obstructive pulmonary disease, and age (Table 23.1). Based upon the total number of points, five classes were created with an increasing predicted risk of respiratory failure as classes advance. Table 23.2 demonstrates the high correlation between the phase I and phase II studies among the different classes of patients. The strength of this study was that patient characteristics and outcomes were prospectively obtained, and overall, this provides a useful guideline to help assess respiratory risk preoperatively.

While few studies present data of prospective risk analysis of pulmonary complications in patients undergoing aortic or great vessel surgery, Money *et al.* retrospectively evaluated 100 consecutive patients undergoing thoracoabdominal aortic aneurysm repairs [23]. In addition to showing that patients who developed respiratory failure had a significantly higher mortality rate compared to those without respiratory failure (42% vs. 6%; $p < 0.001$), they also found that age, type of aneurysm, excessive intraoperative blood transfusion, creatinine elevation, and postoperative pneumonia were independent factors predicting respiratory failure. Of the patients who underwent preoperative pulmonary function testing, the forced vital capacity and forced

Table 23.2 Respiratory failure risk index scores for phase I and phase II patients.

Class	*Point total*	*n(%)*[a]	*Predicted probability of PRF (%)*	*Phase I (% RF)*	*Phase II (% RF)*
1	≤10	39 567 (48%)	0.5	0.5	0.5
2	11–19	18 809 (23%)	2.2	2.1	1.8
3	20–27	13 865 (17%)	5.0	5.3	4.2
4	28–40	7 976 (10%)	11.6	11.9	10.1
5	>40	1 502 (2%)	30.5	30.9	26.6

Source: From Ref. [24]. Permission request submitted to Lippincott Williams and Wilkins.
PAF, postoperative respiratory failure.
[a]Number of phase I subjects in each risk class.

expiratory volume in 1 second were significantly lower in the patients with postoperative pulmonary complications.

Patients undergoing aortic surgery who have a history of chronic obstructive pulmonary disease (COPD) can experience significant postoperative morbidity. Prolonged ventilator dependency, the need for a tracheostomy, and pneumonia are not infrequent events in this patient population. However, overutilization of antibiotics preoperatively to treat tracheobronchial colonization can increase the risk of drug-resistant bacterial strains that can lead to significant life-threatening infectious complications postoperatively. We recommend placing COPD patients on antibiotics preoperatively only if they have a recent history of increased sputum production or a productive cough. For those patients who are actively wheezing, a short course of oral steroids can be considered. Beyond these specific measures, we ensure that all of our COPD patients are on a standard regimen of bronchodilators preoperatively. For those patients who are failing to wean from the ventilator in a routine fashion postoperatively, and particularly if they are wheezing and have no obvious pneumonia or other treatable cause of pulmonary failure such as pleural effusions or pulmonary edema, we again consider the use of steroids. Once these patients are extubated, we recommend an aggressive regimen of incentive spirometry and airway clearance maneuvers, and careful attention to proper fluid balance and diuresis.

Renal complications

Because of various definitions used to diagnosis postoperative renal failure, the exact incidence in aortic surgery is difficult to determine. Studies have used such definitions as a 25% reduction in the creatinine clearance, postoperative serum creatinine exceeding 3 mg/dL in patients with normal

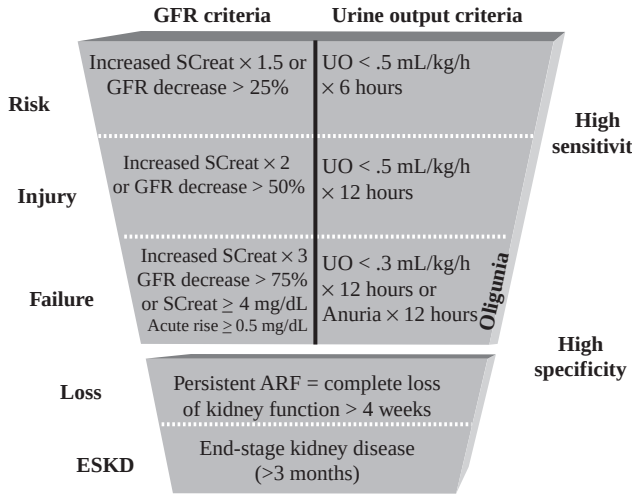

Figure 23.1 RIFLE criteria. Proposed classification scheme for acute renal failure (ARF). The classification system includes separate criteria for creatinine and urine output (UO). A patient can fulfill the criteria through changes in serum creatinine (SCreat) or changes in UO, or both. GFR, glomerular filtration rate; ARF, acute renal failure. (*Source*: From Ref. [34]. By permission of Dr Bellomo and BioMed Central.)

baseline levels, increase in serum creatinine to 50% above baseline, the need for hemodialysis, and most recently the RIFLE criteria [30–34]. RIFLE is an acronym that stands for Risk of renal dysfunction, Injury to the kidney, Failure of kidney function, Loss of kidney function, and End-stage kidney disease. This is a renal failure classification model developed during a 2-day international conference with a goal of standardizing the definition of acute renal failure [34]. See Figure 23.1.

Using RIFLE criteria, Arnaoutakis *et al.* performed a retrospective cohort study to assess acute renal failure in aortic arch operations [35]. A total of 267 patients undergoing hypothermic circulatory arrest for aortic arch operations were assessed over a 5-year period. They found an incidence of postoperative acute renal failure of 48%. Independent risk factors for renal failure included hypertension, chronic kidney disease, transfusion requirement of greater than 5 units of packed red blood cells, and ratio of admission creatinine/MDRD (Modification of Diet in Renal Disease) predicted creatinine greater than 1. Although the incidence of acute postoperative renal failure was quite high in the study, all patients had aortic operations under circulatory arrest and 89% had aprotinin (Trasylol, Bayer Healthcare, Pittsburgh, PA, USA) used during the case.

To identify risk factors associated with postoperative renal failure in vascular surgery patients, Godet *et al.* prospectively studied 475 consecutive patients undergoing thoracoabdominal surgery over a 12-year period [36]. Their definition for development of acute renal failure was a postoperative

serum creatinine concentration greater than 150 μmol/L with normal preoperative renal function (approximately 1.7 mg/dL) or an increase in postoperative serum creatinine greater than 30% of preoperative level in patients with chronic renal dysfunction. Overall, 25% of patients developed postoperative renal failure and 8% required hemodialysis. From multivariate analysis, age greater than 50 years old, preoperative serum creatinine greater than 120 μmol/L (1.36 mg/dL), left kidney ischemia greater than 30 minutes, and a transfusion requirement greater than 5 units of packed red blood cells or greater than 5 units of cell-saver volume were predictive of postoperative renal failure. Predictive factors for postoperative hemodialysis included the following: age greater than 50, transfusion greater than 5 units, packed red blood cells, and preoperative serum creatinine greater than 120 μmol/L.

Patients with aortic pathology, including aneurysmal disease, are believed to have a higher incidence of renal failure. Hagiwara *et al.* retrospectively reviewed 350 patients with aortic aneurysms to examine the incidence of renal failure and found that 90 patients (25.7%) had chronic renal failure as defined by a GFR of less than 60 mL/min for at least a 6-month duration [30]. After a 30-month follow-up, 117 patients (33.4%) had developed renal failure. Independent risk factors for chronic renal failure included age greater than 64, hypertension, and multiple aneurysms. Of the 350 patients studied, 160 patients underwent an aortic surgical procedure. From this group of patients, 44 patients (27.5%) developed postoperative renal failure, with postoperative renal failure being defined as a serum creatinine level increase of greater than 1.5 times or a postoperative glomerular filtration rate (GFR) decrease greater than 25%. Independent risk factors for acute renal failure included dissecting aneurysms, elevated preoperative serum creatinine levels, and duration of operation.

Although endovascular procedures in theory have less cardiac and pulmonary morbidity than traditional open aortic procedures, there is, however, a significant risk of renal complications resulting from endovascular aortic procedures that is most often due to contrast-enhanced nephropathy. To better assess this association, Eggebrecht *et al.* retrospectively evaluated 97 patients who underwent thoracic aortic stent grafts from July 1999 to October 2005 [37]. Of this group, 45% had preoperative chronic kidney dysfunction as defined by a GFR less than or equal to 60 mL/min/1.73 m^2. They defined postoperative renal failure as an increase greater than or equal to 25% and/or greater than or equal to 0.5 mg/dL rise in preprocedure serum creatinine at 48 hours postprocedure. The contrast agent for the procedure was a nonionic, low-osmolar contrast medium (Ultravist 350, Schering, Berlin, Germany) and patients received approximately 307 +/− 188 mL. The incidence of renal failure postoperatively was 34% (33 patients), with 3 requiring hemodialysis. From multivariate analysis, ASA (American Society of Anesthesiologists) class greater than three and duration of the procedure were found to be independent predictors of postoperative renal failure. Patients developing renal failure postoperatively had a significantly higher 30-day and 1-year mortality.

Endovascular approaches

Endovascular approaches to thoracic aortic pathology are rapidly evolving. Follow-up data from the initial multicenter trials continue to lengthen, and the results thus far show endovascular aortic repair to be a safe alternative to open repairs [38, 39]. With this new technology for aortic intervention comes a new set of previously unrecognized complications. These complications range from poor preprocedural planning to technical misadventures that can occur during the procedure, to failure of the devices remotely after the procedure. Although experience with endovascular aortic repair is still in its infancy, we continue to find innovative ways to treat and/or prevent these new and unusual complications.

During this new era of endovascular aortic intervention, strokes unfortunately, are not an uncommon complication. From the initial series of thoracic aortic stents, stroke rates ranged from 2% to 8% [38–41]. Gutsche *et al.* recently reviewed University of Pennsylvania data on strokes during thoracic stent graft trials occurring between 1999 and 2006 [42]. A total of 171 patients had thoracic aortic stent grafts placed during this time. This group was subdivided into three groups depending on the location of the thoracic aorta that was treated: extent A group required coverage of the proximal descending thoracic aorta ($n = 52$), extent B group underwent coverage of the distal descending thoracic aorta, and extent C group had the entire descending thoracic aorta treated. A total of 9 (5.8%) strokes were encountered in this series, and eight of these occurred within 24 hours of the operation. The mortality rate associated with a stroke was significant at 33%. Extent A or C coverage, a history of a prior stroke and CT scan revealing severe atheromatous disease of the aortic arch was associated with a postoperative stroke. In addition, combining a prior history of a stroke with extent A aortic coverage resulted in a 60% incidence of a stroke. Importantly though, those requiring coverage of the left subclavian artery, regardless of a carotid to subclavian bypass, was not associated with an increased risk of perioperative stroke.

Tommaso *et al.* evaluated their experience with endovascular repair of the descending thoracic aorta in 51 patients over a 4-year period (2001–2005) [43]. In 20 patients (39%), the entire descending thoracic aorta (from the left subclavian artery to the celiac axis) was stent grafted. In this series, there were no deaths, surgical conversions, or paraplegia. Procedure-related complications occurred in four patients and included three peripheral vascular complications requiring iliac to femoral artery bypass, and one type I endoleak. Interestingly, this type I endoleak spontaneously resolved after 9 months.

One of the more rare yet serious complications seen with thoracic aortic stent grafting is collapse of the device. This is most commonly a result of placing a slightly oversized device in a tightly curved arch, allowing a small portion of the device to extend out from the lesser curvature into the lumen of the aorta. This creates a protruding leading flap of the device, and with enough aortic pressure and lack of radial hoop strength of the device, the device

collapses or "in-folds." Although most commonly a problem with stent grafts deployed in the aortic arch, this is not the only location where we have seen stent graft collapse. Recently, we have encountered an asymptomatic stent graft collapse in the mid-descending thoracic aorta diagnosed on routine surveillance CT scan 48 hours postprocedure. This patient, as all patients we have encountered with stent graft collapse, was successfully treated with a Palmaz (Cordis Endovascular, Warren, NJ, USA) stent. Hinchliffe *et al.* recently reported on a multicenter European case series of thoracic aortic stent graft collapse between 2003 and 2006 [44]. A total of seven stent grafts were found to be collapsed, or "in-folded" over this 3-year period from five experienced endovascular centers. All seven cases involved stents in the aortic arch, and all were diagnosed within 3 months of the index procedure. Six patients had a Gore TAG device (W.L. Gore and Associates, Evry, France) and one patient had a Zenith (Cook Medical Incorporated, Bjaeverskov, Denmark) stent graft. Interestingly, four of the seven patients had at least one postoperative CT scan that showed an intact stent without evidence of an endoleak, migration, or stent graft collapse. The one common variable to these seven cases was the presence of poor position of the stent in terms of position along the lesser curvature of the arch. Six of these cases were treated using endovascular technology, one with a second stent, and five with angioplasty and a balloon expandable stent placed in the proximal stent graft. There was one patient who underwent an axillary-bi-femoral bypass because of the inability to access the device with wires and catheters, and who was otherwise not medically fit to undergo an open thoracic aortic repair.

Endoleaks represent another difficulty of unknown significance encountered with current stent graft technology. Five types of endoleaks have been described (Figure 23.2) [45]. A primary endoleak refers to an endoleak identified within the first 30 days of implantation and anything thereafter is referred to as a secondary endoleak. The incidence of endoleaks appears to be improving with time as experience is gained, with first-generation stent grafts having a primary and secondary endoleak rate of 20% and 21%, respectively [46], and second-generation stent grafts having an incidence of 7% and 7%, respectively [46, 47]. Fortunately, the majority of these leaks can be repaired with additional endovascular procedures, sparing the patient from a conversion to an open operation. Riesenman *et al.* reported on their experience of 50 consecutive stent grafts of the descending thoracic aorta from October 2000 to May 2004 [48]. The overall endoleak rate was 20%, with half being primary and half secondary endoleaks. Of the five primary endoleaks (one type 1a, two type 1b, and two type III), four were treated with a second endovascular procedure, with the type III endoleak patients receiving additional stents and the type 1a and one of the type 1b patients being treated with balloon angioplasty to remold the end of the stent graft. Of the five secondary endoleaks (three type Ib, one type II, and one type III), three patients underwent a second endovascular procedure and all three required an additional stent graft component. Direct aneurysm sac puncture with embolization of branch

Type	Subtype	Description
I	a	Leak from the proximal end of the stent
	b	Leak from the distal end of the stent
II		Leak from collateral vessels, that is, lumbar, inferior mesenteric, hypogastric
III		Leak between two graft components
IV		Leak from a porous graft
Unknown		Leak from an unidentified source

Figure 23.2 Classification of endoleaks.

vessels, or infusion of fibrin glue or similar compounds, is another means for treating type II endoleaks that is being employed more commonly. However, large series reporting the results of these techniques and long-term outcomes data are not available.

The utility of debranching procedures to facilitate the creation of landing zones for stent grafting is being done more frequently as a means to avoid more extensive direct aortic operations. Such debranching procedures are often major operations in and of themselves, and the long-term durability of these procedures is not known. Long-term surveillance is not ameliorated with debranching procedures, and the ability to provide secondary percutaneous interventions may be severely compromised. It is our position to limit the use of debranching procedures at the present time, and we prefer to perform direct aortic reconstruction for those patients with truly inadequate landing zones for present stent graft technology.

Conclusions

Aortic and great vessel operations are associated with significant morbidity and mortality. Although we continue to make therapeutic advances utilizing improved technology, there remains a wide range of complications that occur with such invasive procedures. As new techniques are developed to minimize the impact and frequency of these complications, results are improving. Recently, endovascular approaches to aortic pathology have changed the way we approach aortic disease. Endovascular procedures are associated with a different set of complications, and as we encounter these complications, we must develop new and creative ways to treat and prevent them from occurring. Fortunately, most technical complications of endovascular aortic procedures are treatable with secondary percutaneous interventions. While open aortic operations are still required for many patients with aortic diseases, endovascular approaches may soon become the gold standard to treat aortic and great vessel pathology. It is imperative for all of us to maintain our skill set and knowledge at an appropriate level to allow optimal treatment of these very ill patients.

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