Peter Slinger *Editor*

Randal S. Blank · Javier Campos
Jens Lohser and Karen McRae
Associate Editors

Principles and Practice of Anesthesia for Thoracic Surgery

Second Edition

Springer

EXTRAS ONLINE

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The Editor would like to thank the members of his family for their never-ending support and patience.
Photo Left to right:
Back row: Colin (son-in-law), Eric (baby, grandson), Lee (daughter), Peter (editor), Rusty (wife), Robyn (daughter-in-law), Luke(son).
Front row: Reagan (grand-daughter,) Jake (grandson), Bruce (Luke's dog)

Preface

It has been 8 years since the Associate Editors (Randall Blank, Javier Campos, and Karen McRae) and I assembled the first edition of *Principles and Practice of Anesthesia for Thoracic Surgery*. In this time period, there has been considerable evolution in the anesthetic management of patients requiring anesthesia for non-cardiac intrathoracic diagnostic and therapeutic procedures. We felt that it would be useful to update and expand the original text for practitioners of thoracic anesthesia at all levels including Staff Anesthesiologists, Residents, Fellows, Nurse Anesthetists, Nurse Practitioners, Anesthesia Assistants, and other Allied Health Professionals. We welcome the addition of Jens Lohser, from the University of British Columbia, as an Associate Editor for this second edition.

Among the major advances that we address in this new edition, we include the expanded role of ultrasound beyond transesophageal echocardiography (Chap. 30): Lung ultrasound has evolved from a curious pattern of artifacts to an essential clinical role in chest trauma and management of pleural effusions (Chap. 28). Ultrasound is now an established tool for the placement of many types of central and peripheral vascular access (Chap. 29). And, ultrasound has permitted the development of several new regional anesthetic blocks (e.g., serratus anterior and erector spinae, Chap. 59) that are useful modalities for management of postoperative pain.

Also new in this edition is the role of extracorporeal membrane oxygenation (ECMO) (Chap. 27) in thoracic anesthesia. Veno-venous ECMO is becoming an established therapeutic option for management of intraoperative hypoxemia in complex types of lung and airway surgery and in whole lung lavage. Venoarterial ECMO is rapidly replacing cardiopulmonary bypass as the main method of extracorporeal lung support in lung transplantation (Chap. 47).

There have been major advances in postoperative pain management for thoracic surgery in this decade. In addition to the new blocks mentioned above, the book covers the expanded use of paravertebral blocks and the use of long-acting local anesthetics (Chap. 60). Also, there have been a variety of new bronchial blockers and modified double-lumen tubes developed that facilitate lung isolation in patients with difficult airways (Chaps. 16, 17, and 18).

We would like to welcome the first Authors of new chapters.

Among these are:

- Daniel Sellers (University of Toronto, Intraoperative Extracorporeal Lung Support for Pulmonary and Airway Surgery, Chap. 27)
- Rebecca Klinger (Duke University, Perioperative Fluid Management in Thoracic Surgery, Chap. 21)
- Danielle Shafiepour (McGill University, Trouble-Shooting One-Lung Ventilation, Chap. 26)
- Nathan Ludwig (University of Western Ontario, Lung Ultrasound, Chap. 28)
- Natalie Silverton (University of Utah, Ultrasound for Vascular Access, Chap. 29)
- Alexander Huang (University of Toronto, Pulmonary Resection in the Patient with Pulmonary Hypertension, Chap. 34)
- Helen Lindsay (New Zealand, Anesthesia for Open Descending Thoracic Aortic Surgery, Chap. 41)

- Andrew Levin (Stellenbosch University, Cape Town, South Africa, Bronchopleural Fistula, Chap. 43)
- Maureen Cheng (Cambridge University, Anesthesia for the Patient with a Previous Lung Transplant, Chap. 48)
- Emily Teeter (University of North Carolina, Enhanced Recovery After Thoracic Surgery, Chap. 52)
- Hadley Wilson (University of North Carolina, Trouble-Shooting Chest Drains, Chap. 58)
- Wendell H. Williams III (MD Anderson Cancer Center, Long-Acting Local Anesthetics for Post-Thoracotomy Pain, Chap. 60)

We would also like to welcome several new first Authors of previous chapters, including Drs. Amanda Kleiman (University of Virginia, Non-respiratory Functions of the Lung, Chap. 7), Javier Lasala (MD Anderson Cancer Center, Intravenous Anesthesia for Thoracic Procedures, Chap. 12), Lorraine Chow (University of Alberta, Anesthesia for Patients with Mediastinal Masses, Chap. 14), Daniel Tran (Yale School of Medicine, Lung Isolation in Patients with Difficult Airways, Chap. 18), Jennifer Macpherson (University of Rochester, Intraoperative Ventilation Strategies for Thoracic Surgery, Chap. 22), Florin Costescu (McGill University, Anesthesia for Patients with End-Stage Lung Disease, Chap. 31), George Kanellakos (Dalhousie University, Thoracic Surgery for Morbidly Obese Patients and Patients with Obstructive Sleep Apnea, Chap. 33), Valerie Rusch (Memorial Sloan Kettering Cancer Center, Pancoast Tumors and Combined Spinal Resections, Chap. 37), Swapnil Parab (Tata Memorial Hospital, Mumbai, India, Thoracic Anesthesia in the Developing World, Chap. 42), Timothy Maus (UC San Diego, Anesthesia for Pulmonary Thromboendarterectomy, Chap. 49), Michael Hall (University of Pennsylvania, Anesthetic Management of Post-Thoracotomy Complications, Chap. 53), and Wendy Smith (UC San Francisco, Postoperative Respiratory Failure and Treatment, Chap. 54).

New to the second edition is the incorporation of video. Relevant video clips will be available online to readers of the print text. For the online text, streaming video clips will allow the reader to point and click to see techniques as they are described. This is particularly useful for ultrasound-guided procedures and lung isolation.

Personally, I would like to thank the returning Authors and Coauthors from the first edition for the thorough updates of their previous chapters. Thank you to the Associate Editors for their hard work and support. And, thank you to the Editors at Springer Clinical Medicine, Daniel Dominguez and Becky Amos, for their encouragement.

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Peter Slinger

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Part I

Introduction

History of Thoracic Anesthesiology

1

Ian Conacher

Key Points

- Because of the concern relating to the natural history of pneumothorax, the development of a thoracic surgery discipline comparatively was late.
- Tuberculosis was the stimulus to overcome concern and caution.
- Control of contaminating secretions was an early anesthesia objective.
- Rigid bronchoscopy, lung separation, and positive-pressure ventilation are milestones of significance.
- Modern materials have enabled considerable advances in essentially early ideas.
- The anesthesia challenge of surgery of respiratory failure is to counteract the negative effects of positive-pressure ventilation.
- Surgery for lung cancer remains the bulk of workload.

Introduction

Infantry in disciplined armies like those of the Romans were trained to inflict a penetrating stab injury to the chest wall. Early depictions capture the paradox of a small and bloodless injury inevitably being fatal: and a dignity to a transition into another world as deep to the wound the lung collapses, respiration becomes paradoxical, and carbon dioxide retention and hypoxia ease the passing. In the nineteenth century, as surgery was advancing apace because of antisepsis and anesthesiology, it was opined that the surgeon's knife would for these old reasons inevitably lead to the death of the patient: surgically attempting to incise into the thorax was something of a taboo, only to be breached by *Ferdinand Sauerbruch (1875–1951)* little more than a century ago (Fig. 1.1).

The late beginning to the thoracic surgery discipline is overlooked. The author occasionally assisted the distinguished *Phillip Ayre (1902–1979)* who had worked with a surgical collaborator of Sauerbruch. This was *Laurence O'Shaugnessy (1900–1940).* A casualty of the Second World War, he left to posterity one of the earliest surgical methods of treatment for angina and distinctive forceps that graced thoracic surgical instrument trays for 60 years and has been modified for minimal access use (Fig. 1.2).

The fatal process – wound, pleural penetration, lung collapse, respiratory, and cardiac arrest – was interrupted with construction of an operating environment that counteracted the elastic force that paralyzes respiratory function. With encasement of the surgeon and patients' torso in a negative-pressure chamber, atmospheric pressure (now positive in physiological terms) operated at the patient's exposed mouth and prevented the lung collapsing as soon as parietal pleura was breeched. Expired tidal ventilation and gas exchange can continue to counter the toxic effect, described as "pendelluft," of moving physiological dead space gas back and forth between the lungs. Accumulation of carbon dioxide in the self-ventilating patients was delayed and albeit limiting operating time was enough to open the historical account of thoracic surgery.

The Sauerbruch technique was replaced by more efficient methods to reverse intrapleural dynamics and based on supra-atmospheric pressures applied to the airway – a move recognizable in modern day practices of tracheal intubation and positive-pressure ventilation. The change is typical of an early phenomenon: the thoracic discipline attracted inspired minds, with ingenious ideas to build on templates of pioneers. Here are to be found stories of great physiologists, physicians, surgeons, and anesthesiologists without whom, for instance, the groundwork for a diversification into cardiac surgery would have been significantly delayed. Indeed in many countries, the latter services still are rooted in establishments that once were sanatoriums, serving the needs of early patients for chest surgery.

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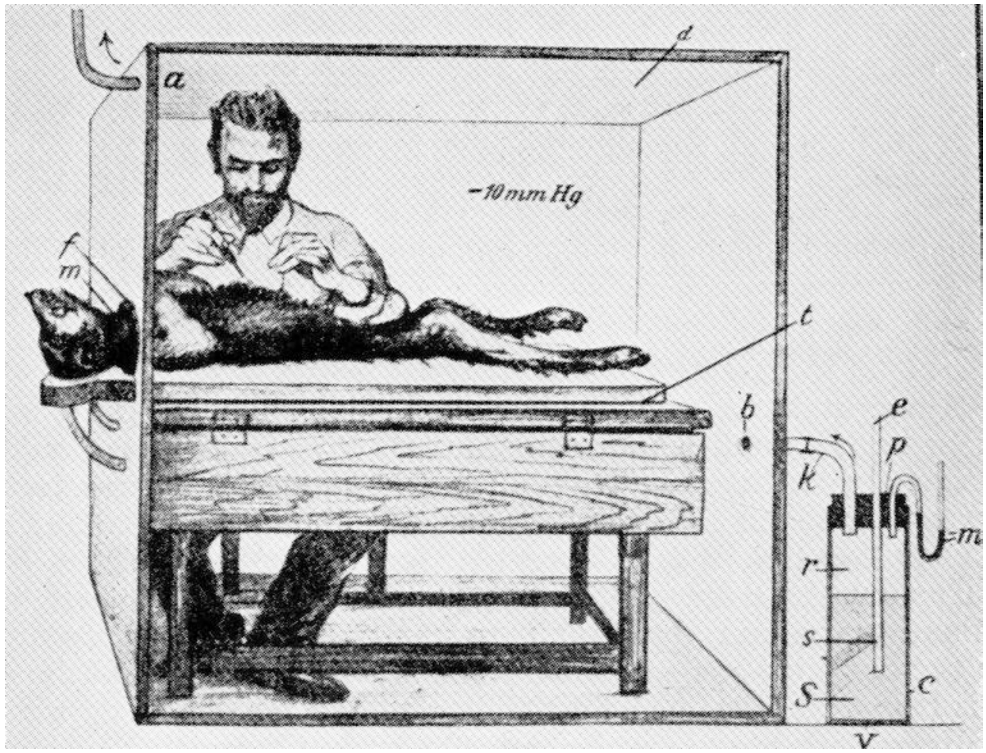


Fig. 1.1 A diagram of Sauerbruch's negative-pressure chamber for thoracic anesthesia. The animal or patient's torso and the surgeons were enclosed in an airtight chamber evacuated to −10 cm H_2O pressure. The subject was then anesthetized breathing air-ether spontaneously from a mask. When the thorax was opened, the lung did not collapse and hypoxemia was averted, although hypercarbia would gradually develop due to pendelluft. This marked the beginnings of elective thoracic anesthesia and surgery. (From Mushin W, Rendell-Baker L. The principles of thoracic anaesthesia. Oxford: Blackwell Scientific Publications; 1953.)

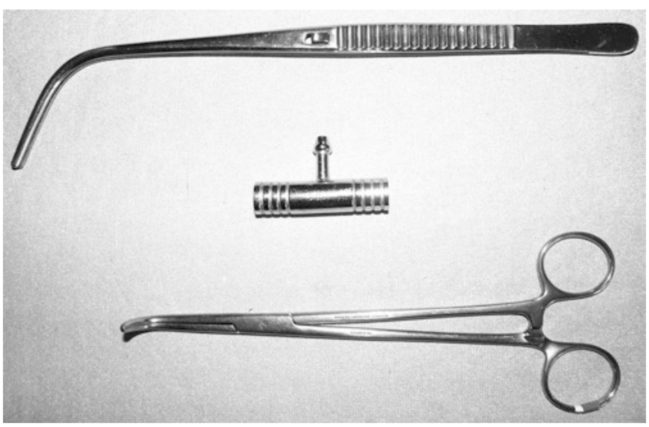


Fig. 1.2 Thoracic ephemera. From top to bottom: Krause's Forceps, Ayres "T" piece, O'Shaughnessy Forceps

In each development, an anesthesiologist of the day has had to innovate, adapt, and change with new ideas, materials, and advances being presented to him or her. A formative beginning with candle power disappeared with antimicrobial therapy but leaves a legacy of thoracoscopy, lateral thoractomy, lung separators, and pain relief techniques that are but little modified.

Paradigm shifts are usually marked by the two World Wars of the twentieth century. Though these are defining elements of any historical analysis, and certainly colored the individuals who are part of the story, developments in thoracic surgery that now govern modern practice are better seen in the light of changes in the medical challenges of disease which changed coincidentally at the same time points.

Ages of Thoracic Surgery

Surgery for Infective Lung Disease

The nineteenth century, a time of great population and societal movement particularly in and from Europe, was blighted by the "white plague" (tuberculosis), an indiscriminate killer – irrespective of class, wealth, national boundaries, and unstoppable, a foreshadowing of AIDS: a heroine in the throes of consumption, a last hemoptysis, death – stuff of opera. Into this hopelessness strides the surgeon to deal with pulmonary cavities, septic foci, decayed and destroyed lung, bleeding points, and copious, poisonous secretions that were more than capable of drowning the patient. Surgical repertoire after the Sauerbruch revelation was the artificial pneumothorax, empyema drainage, plombage (insertion of inert material into the thoracic cavity to promote lung collapse as therapy for tuberculosis), phrenic nerve crush, the thoracoplasty, and some tentative steps at resection – ordeals staged over days and weeks but with an accrual of lifesaving consequences for countless (Fig. 1.3).

With no mechanisms of control of secretions and an ever-present danger of respiratory failure, standards for anesthesiology were sedation with opiates, topical, regional, and field blockade with local anesthetics to preserve self-ventilation so that cough and the ability to clear the airway were not lost.

Operating position became important. That of Trendelenburg was most effective to ensure that secretions, blood, and lung detritus drained gravitationally and not into

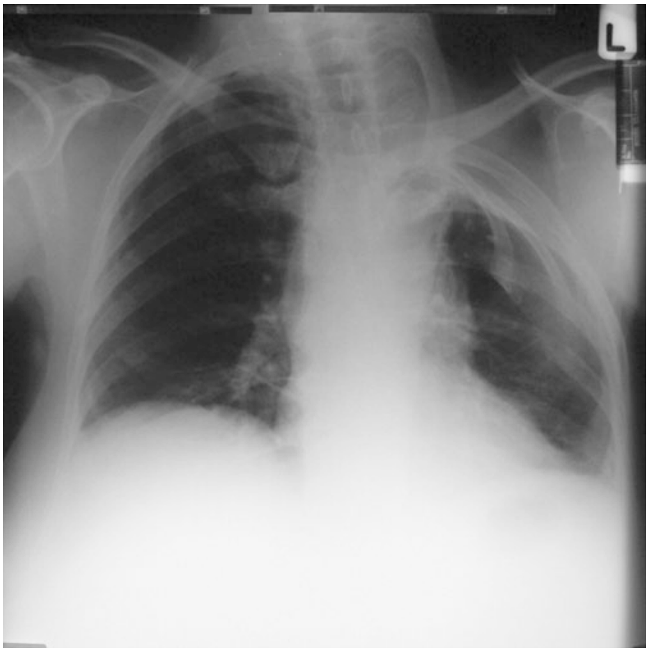


Fig. 1.3 Chest X-ray of a left-sided thoracoplasty, the ribs of the upper left hemithorax have been resected to promote left upper lobe collapse for tuberculosis therapy

the nonoperated lung. But, in the cachectic and septic sufferer of pulmonary tuberculosis or bronchiectasis, adoption of such steep head-down postures could prove fatal. The prone and semiprone positions were gentler and less compromising. Surgeons got used to operating and approaching the lung and its constituents through a posterior thoracotomy. This spawned the posterolateral thoracotomy, once tracheal intubation techniques enabled alternative, nongravitational ways of dealing with the secretion problem. The lung, esophagus, and heart became grist to the thoracic surgical mill.

As the era closed, the anesthesiologist (and the dawn of the specialist was at hand) had an experience of nitrous oxide and several volatile agents other than ether, notably chloroform and cyclopropane. Insufflation techniques, tracheal intubation, and rudimentary bronchial blocking techniques, which required a skill in rigid bronchoscopy, were tools of the expert. Several were using assisted ventilation before the advent of muscle relaxants. Prototype endobronchial tubes, bronchial blockers, and early positive-pressure ventilation techniques were in position for a new age – ushered in with curare.

There is no greater symbol of the transition than the pneumonectomy of the British King, *George VI (1895–1952).* Operated on in 1951 – for lung cancer – by a surgeon (*C. Price Thomas (1893–1973)*) who was credited with his own operation (sleeve resection) for tuberculosis, the anesthesiologist (*Dr R. Machray*) had devised his own tracheal tube (but on the occasion used a Thompson bronchus blocker) and wielded measured doses of diamorphine and pethidine, nitrous oxide, and the new agent, curare. And in the wings, spurred by intraoperative problems with ventilation, a trainee anesthesiologist (*William Pallister (1926–2008)*) was inspired to invent a new endobronchial tube specifically for the surgeon and his operation to avoid such critical incidents in the future. The surgeon later developed lung cancer for which he was operated on! The cigarette was yet to be seen as the cause and that this particular blight was largely man-made.

Surgery for Lung Cancer

Pulmonary resection for lung cancer came to dominate operating lists as the tuberculosis hazard receded to a point of rarity in developed countries with advances in public health that followed the Second World War. The favored method was general anesthesia with volatiles such as the new agent halothane, lung separation – commonly with double-lumen tubes – muscle relaxants, and, after the polio epidemics of the 1950s, positive-pressure ventilation with increasingly sophisticated ventilators. The Academic of the day, having acquired scientific tools, was beginning to recognize and investigate the subtle pathophysiological changes wrought by one-lung anesthesia.

In general, advances were defined by greater understanding of pulmonary physiology, limits and limitations of surgery particularly degree of resectability, and the fitness of patients to withstand ordeals of process, and more regard for quality of postresection existence. The crude practice of inserting a blocker through a rigid bronchoscope under topical anesthesia applied with Krause's Forceps, to test for the potential to survive a pulmonary resection, could be abandoned! Besides safeguarding the technological skills of an earlier era, the anesthesiologist needed to acquire a bedside expertise of the potential for respiratory failure to develop in a particular patient, based on simple pulmonary function tests (wet spirometry). In this era predating a foundation or philosophy for prolonged recovery with ventilator support and postoperative care resource, forecasting was on the basis that fatalities were theoretically due to carbon dioxide retention or right heart failure if excess lung was resected in reaching for a cure for a cancer: in practice sepsis and renal failure usually proved terminal.

The ending of this work pattern followed advances of plastics technology on equipment, fiber optics on diagnostics and operating instruments, and computers on monitoring and performance. Surgery was moving into an age that had a patient demand to push operability beyond limits established for cancer. This desire was to be met with larger resource for intensive levels of postoperative care.

Although advances were truly innovative, these were fraught with risk. For a perspective on this, recall that pulse oximeters were experimental not universal and end-tidal carbon dioxide measurement nonexistent: operational decisions depended on blood gas monitoring with unsophisticated and slow automated systems and the occasional use outside the laboratory of Swan-Ganz type pulmonary flotation catheters.

Surgery for Respiratory Failure

Defining elements include transplantation but also revisits to treatment of emphysema (which had with chronic bronchitis reached significant proportions in developed countries) and technological and material advances for trachea-bronchial disease which heretofore were off limits to all but a few establishments with special expertise and cardiopulmonary bypass technology.

Orthotopic lung transplantation had been attempted in extremis (1963), but success in terms of long-term viability was not to be achieved for another two decades (1986). A new immunosuppressant therapeutic era was to enable further, and this time, successful efforts. Much of the credit goes to the Toronto group, under Dr. Joel Cooper, whose selection and management templates resolved problems previously encountered by attempting to treat paraquat poisoning, routine use of corticosteroids for airway disease, tracheobronchial dehiscence, and reimplantation. Matching of lung preservation techniques to those for cardiac donors was a final step from experimental to mainstream and to the current healthy state of a thoracic organ transplant discipline.

Chronologically, not far behind, is lung volume reduction surgery, driven by many of the same innovators. Historically, this was just a revisitation of old ideas and not a monumental surgical advance; but the lessons learnt were in particular for anesthesiology. In learning to deal with emphysema lung pathophysiology, a "downside" of positive-pressure ventilation was encountered with great frequency. The prevention and treatment of dynamic hyperinflation scenarios ("breath stacking") is now, after a century, as big a challenge as that of "pendelluft" breathing was in its day.

Lung Separators

Three systems have evolved to facilitate one-lung ventilation: bronchus blocker, endobronchial tube, and double-lumen tube. The first two were of concept and had prototypes about the same time. Gale and Waters in 1931 have the credit for intubation of the contralateral bronchus prior to pneumonectomy: Crafoord and Magill as firsts for bronchial blocking. The double-lumen tube is a later development and as concept was taken from catheters, most notably the Carlens, devised for bronchospirometric research, assessment, and investigation.

Devices were manufactured out of red rubber, and over the years many adaptations were made: right- and left-sided versions, carinal hooks, right upper lobe slots, and extra-inflatable cuffs, cuffs of red rubber and of latex rubber, net-covered – to mention but a few.

The Blocker Story

It is to the particular genius of *Ivan Magill (1888–1986)* that the bronchus blocker is owed. With minor modifications it became a dominant technique for practitioners, use of which, as mentioned, had become a test for fitness for operation. Inserted through a rigid bronchoscope, the blocker could be placed accurately in the most complex of anatomical distortions wrought by tuberculosis. The state-of-the-art device was that of *Vernon Thompson (1905–1995)* (Fig. 1.4). However, endobronchial tube availability and the versatility of double-lumen tubes meant that by the latter part of the twentieth century, there were few but a dedicated band of practitioners with the skill to place and use blockers effectively and first choice status was lost. Plastics and fiber optics led to reinvention for the twenty-first century. "Univent," Arndt, and Cohen systems follow in quick succession as the concept was revitalized.

The Endobronchial Tube Story

These very obvious adaptations of tracheal tubes gave anesthesiologists a range of devices that served purpose for half a century. That of Machray was a long, single-cuffed tracheal tube and was placed in the left main bronchus under direct vision using an intubating bronchoscope as introducer

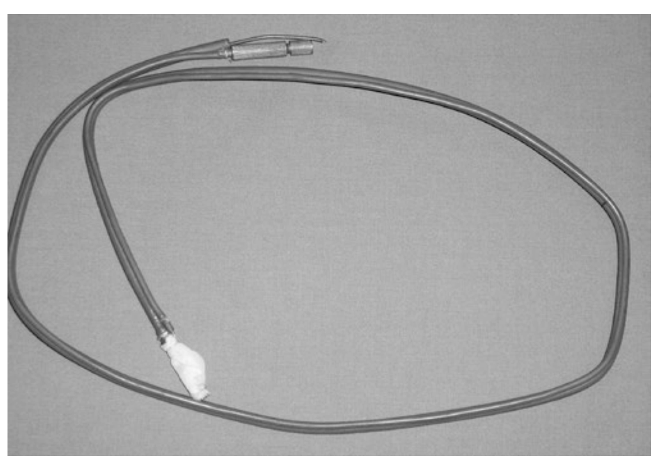


Fig. 1.4 Vernon Thompson bronchus blocker (circa 1943)

Fig. 1.5 Machray endobronchial tube and intubating bronchoscope

(Fig. 1.5). Being able to mount these devices on a rigid scope, again a Magill credited idea, defined these tubes. The characteristic facilitated placement in the most distorted of airways and allowed for ventilation through a wide-bore tube, bettered only by using a bronchus blocker outside and beside an endotracheal tube. Left-sided Macintosh-Leatherdale and Brompton-Pallister and the right-sided Gordon-Green were to prove the most enduring.

The Double-Lumen Tube Story

Unlike the other types of lung separators, the double-lumen tube was adapted and adopted rather than invented for the purpose of one-lung anesthesia and ventilation. The prototypes, notably that of *Eric Carlens (1908–1990)*, were for physiological investigation. Models with the ventilation lumens positioned coaxially and anterior-posterior were tried but that of *Frank Robertshaw (1918–1991)* with its side-by-side lumens, anatomical shape, range of size, and low resistance characteristic dominated, to be later reproduced as plastic and disposable materials (e.g., Sheridan, Broncho-Cath) that replaced the increasingly unsuitable and anachronistic red rubber. The right-sided version was actually invented from a Gordon-Green endobronchial tube, the slot of which has remained the most effective device to ventilate the right upper lobe – an efficacy dependent on properties of red rubber (Fig. 1.6).

Plastic and practice penetration by fiberoptic bronchoscopes of decreasing size and increasing sophistication and practicality led to much contemporary discussion about the "blind" placement of lung separators that replaced the tradition of rigid bronchoscopy as an aid to lung separation and bronchial cannulation. Though modern protocols are more fail-safe than reliance on clinical and observational skills, the modern didactic of medicolegality has trumped debate and stifled argument.

Origins of Thoracic Endoscopy

The ancient entertainment of sword swallowing had long demonstrated the feasibility of inserting rigid instruments into the esophagus. In 1895 a scope was first passed through a tracheotomy opening to be quickly followed by

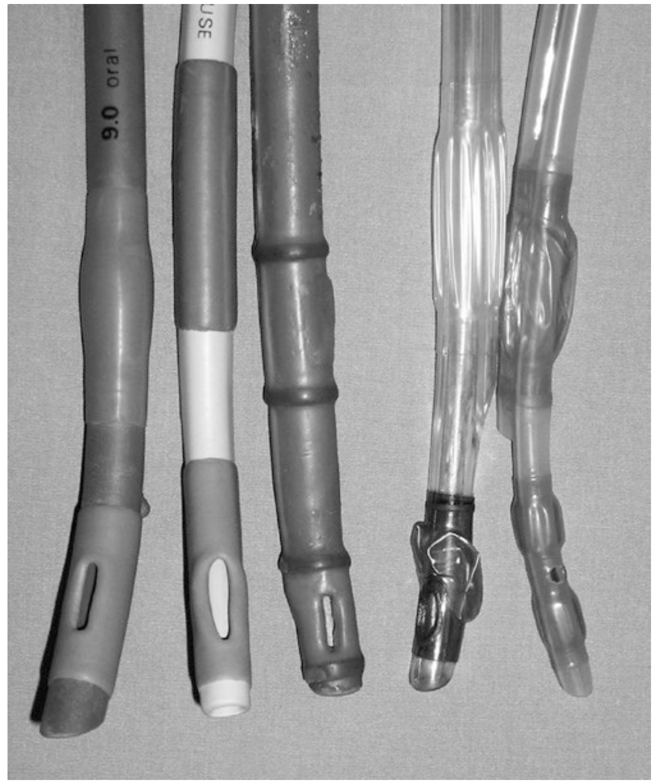
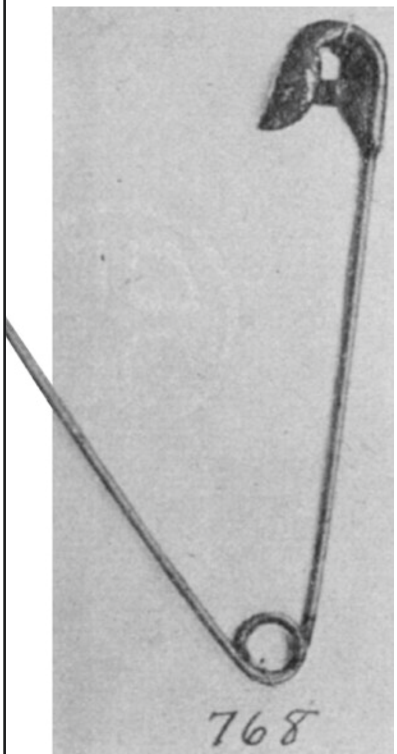


Fig. 1.6 Tubes with right upper lobe ventilation slots. From left to right: Gordon-Green endobronchial, Robertshaw double lumen, Carlens (White model) double lumen, "Broncho-Cath" double lumen, and "Portex" prototype double lumen

endoral attempts but at the limits of proximal lighting systems. *Chevalier Jackson (1865–1958)* was not the originator, but he certainly was a pioneer and the first master of distal lighting systems, with a record on removal of foreign bodies that stands unsurpassed to this day (Fig. 1.7). To him are owed the rules that made the dangerous art of sword swallowing into a scientific tool for therapy and diagnosis both in the esophagus and in the tracheobronchial tree and the subtleties of neck positioning that ensure either the esophagus or trachea is cannulated: a whole philosophy of skill that has been negated by the flexible nature of modern tools.

Now the only indications for rigid bronchoscopy are foreign body removal and occasional stent insertion, but there was a time when rigid bronchoscopy was indispensible for operative assessment, bronchography, diagnostics, insertion of lung separators, postoperative lung toilet, and treatment of bronchopleural fistula. Under careful local anesthetic application, topical, regional, and cricothyroid puncture, the technique could be conducted with such skill that no less an illustrious patient than *Geoffrey Organe (1908–1989)*, the Professor of Anaesthesia, Westminster Hospital, London, was able to declare the experience as "more pleasant than going to the dentist."

Fig. 1.7 A series of safety pins removed from the airway by rigid bronchoscopy. (From Jackson C. Foreign bodies in air and food passages. Charted experience in cases from no. 631 to no. 1155 at the Bronchoscopic Clinic; 1923)

Fbdy. 768 	15 yrs.	Safety-pin open	Right main bron-chus, 3 weeks
Fbdy. 786 	4 yrs.	Safety-pin open	Larynx, point up, 3 days
Fbdy. 794 41 	18 yrs.	Safety-pin open	Right lower lobe bronchus. Point up. 1 yr. 10 mos.

Trying to produce an artificial pneumothorax frequently failed because of adhesions. In 1913, a Swedish surgeon, Hans Christian Jacobaeus, reported on the use of a modified cystoscope to look into the chest and used a second port for instruments, such as probes and cautery, to deal with recalcitrant adhesions. It is not hard to see how this concept has evolved.

Tracheobronchial Stenosis

As technological advance is on the brink of tracheal reconstruction using biological methods, it is important not to forget that this state has been reached by a long and hard struggle to overcome the challenge for surgery and healing inherent in innately poor mammalian vascular supply of the tracheobronchial tree. The era of tracheal resection and repair was to be dominated by *Hermes Grillo (1923–2006*), the Chief of Thoracic Surgery at the Massachusetts General Hospital. There was a brief period of tracheoplasty and silicon replacements, all of which were major anesthesiological undertakings, but developments in stents, largely modeled on similar devices for esophageal stricture, had become prevalent at the end of the twentieth century. Solid-state devices of silicon were replaced by a range of self-expanding ones made of nonreactive and malleable materials such as nitinol which have resulted in less challenging anesthesia scenarios.

Esophageal Surgery

Originally, surgery on the esophagus was very much a development of chest surgery. Several medical cultures retained a linkage late into the twentieth century, but this was largely a technical connection because of commonality of anesthesiological requirements like lung isolation. Most countries have now broken the connection, and the esophagus is largely seen as outside the hegemony of thoracic practice. Cancer, achalasia, and hiatus hernia, once part of the tougher end of the surgical diet, are now treated less traumatically and invasively.

As with pulmonary resection, early developments were based on totemic patients by small teams, whose successes and tribulations sustained knowledge that relief by surgical means ultimately was going to be of benefit to many more. A single case survivor of 13 years after transpleural esophagectomy by *Franz Torek (1861–1938)* in New York in 1913 was a beacon for three decades. The anesthetist was *Carl Eggers (1879–1957)* who administered ether through a woven silk tracheal tube to a self-ventilating patient. In 1941, the world experience of the technique was 17 survivors of 58 patients.

Pain Relief

Modern analgesics can be traced to the coca leaf, opium poppy, and willow bark, but administration other than by ingestion or inhalation needed the hypodermic needle. Spinal injection (1898), intercostal nerve blockade (1906), paravertebral injection (1906), and extradural (1921) are the historical sequence for local anesthetic procedures of context.

Survivors of thoracoplasty operations tell of hearing their ribs being cracked as, in the later stages of the operation, the thoracic cage was rearranged: few attendants were prepared to risk general anesthesia. A specimen technique of Magill's for this operation, first performed in the UK by *Hugh Morriston Davies (1879–1965)* in 1912, included premedication with opiates, supraclavicular brachial plexus block, intercostal nerve block, dermal infiltration of skin incision site and towel clip points as well as subscapular infiltration and much titration of dilutions of adrenalin (epinephrine). *J Alfred Lee (1906–1989)* (author of the classic *A Synopsis of Anaesthesia*, first produced in 1947) states advantages of local as opposed to general anesthesia: reduced risk of spread of disease, better elimination of secretions as cough reflex is not abolished, quicker convalescence because patient is less upset by drugs and needs less nursing care, and abolition of explosion risk.

Paravertebral blockade, first credited to Sellheim, went on to be used for operative pain relief, postthoracotomy neuralgia, and even angina and thoracic pain of unknown etiology. Subarachnoid block enjoyed a period in thoracic surgery, but the "high" nature meant that it was a hazardous technique because of uncontrolled hypotension and suppression of respiration. Epidural anesthesia was limited by the toxicity of agents, hazard of hemodynamic collapse, the short-lived nature of single-shot procedures, and logistics and feasibility of process in the context of hospital environment. Continuous analgesia perioperatively was only realistic with small-bore tubing and got impetus from the link to improved postoperative respiratory function.

Correlation of pain relief and reversal of some of the negative effects of surgery led to recognition that pain relief objectives could be broadened from humanitarian and reactive. A new philosophy has arisen: it is a proactive one to capitalize on observations that pain relief techniques contribute to the healing process by promoting a sense of well-being, preserving gastrointestinal function, improving anastomotic blood flow, and facilitating management of comorbidity.

Conclusion

The impetus for surgical development and advance are all in context, and in none more than thoracic practice is this true: phases, even paradigm shifts, defined by disease, sociology and advances in knowledge, and therapeutics and, in the case of anesthesiology, by drugs, materials, and technology. As historical evolution, much of current practice is recognizable.

A modern age is already characterized by a circumspect use of volatile agents, but predictable forces of surgery are the demand for minimal access and the use of once-only disposable materials that have already seen the demise of much of local infrastructure to process sterile equipment and surgical hygiene. Hospital-acquired infection morbidity is a given, as are epidemics of asbestosis-related pleural-pulmonary disease as this ubiquitous "pathogen" escapes from the twentieth-century confines. A new epidemic, obesity, will gain momentum. Lung cancer treatment options show little sign of being bettered by other than surgical methods. Tuberculosis has a new drug-resistant guise. Could history repeat itself? Many countries, notably in Africa and those previously part of the USSR, have endemic populations harboring and, sadly, nurturing drug-resistant tuberculosis. Some are now contemplating revisiting and revising early surgical techniques (e.g., thoracoplasty) to add to future projects to tackle what has to be one of the most predictable and threatening of microbial conditions with a future to impact on thoracic anesthesiology and on all health-care systems.

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Part II

Preoperative Evaluation

Preanesthetic Assessment for Thoracic Surgery

2

Peter Slinger and Gail Darling

Key Points

- All patients having pulmonary resections should have a preoperative assessment of their respiratory function in three areas: Lung mechanical function, pulmonary parenchymal function, and cardiopulmonary reserve (the "three-legged stool" of respiratory assessment).
- Following pulmonary resection surgery, it is usually possible to wean and extubate patients with adequate predicted postoperative respiratory function in the operating room provided they are "AWaC" (alert, warm, and comfortable).
- Preoperative investigation and therapy of patients with coronary artery disease for noncardiac thoracic surgery are becoming a complex issue. An individualized strategy in consultation with the surgeon, cardiologist, and patient is required. Myocardial perfusion imaging and stress echocardiography are used increasingly in these patients.
- Geriatric patients are at a high risk for cardiac complications, particularly arrhythmias, following large pulmonary resections. Preoperative exercise capacity is the best predictor of post-thoracotomy outcome in the elderly.
- In the assessment of patients with malignancies, the "four M's" associated with cancer must be considered: Mass effects, metabolic effects, metastases, and medications.
- Perioperative interventions which have been shown to decrease the incidence of respiratory complications in high-risk patients undergoing thoracic surgery include cessation of smoking, physiotherapy, and thoracic epidural analgesia.

Introduction

Thoracic anesthesia encompasses a wide variety of diagnostic and therapeutic procedures involving the lungs, airways, and other intrathoracic structures. As the patient population presenting for noncardiac thoracic surgery has changed, so have the anesthetic techniques required to manage these patients. Thoracic surgery at the beginning of the last century was primarily for infectious indications (lung abscess, bronchiectasis, empyema, etc.). Although these cases still present for surgery in the post-antibiotic era, now the commonest indications are related to malignancies (pulmonary, esophageal, and mediastinal). In addition, the last two decades have seen the beginnings of surgical therapy for end-stage lung diseases with procedures such as lung transplantation and lung-volume reduction.

Recent advances in anesthetic management, surgical techniques, and perioperative care have expanded the envelope of patients now considered to be operable [1]. This chapter will focus primarily on preanesthetic assessment for pulmonary resection surgery in cancer patients. However, the basic principles described apply to diagnostic procedures, other types of nonmalignant pulmonary resections, and other chest surgeries. The major difference is that in patients with malignancy, the risk/benefit ratio of canceling or delaying surgery pending other investigation/therapy is always complicated by the risk of further spread of cancer

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during any extended interval prior to resection. Cancer surgery is never completely "elective" surgery.

A patient with a "resectable" lung cancer has a disease that is still local or local-regional in scope and can be encompassed in a plausible surgical procedure. An "operable" patient is someone who can tolerate the proposed resection with acceptable risk. Anesthesiologists are not gatekeepers. Normally, it is not the anesthesiologist's function to assess these patients to decide who is or is not an operative candidate. In the majority of situations, the anesthesiologist will be seeing the patient at the end of a referral chain from chest or family physician to surgeon. At each stage there should have been a discussion of the risks and benefits of operation. It is the anesthesiologist's responsibility to use the preoperative assessment to identify those patients at elevated risk and then to use that risk assessment to stratify perioperative management and focus resources on the high-risk patients to improve their outcome (Fig. 2.1). This is the primary function of the preanesthetic assessment. However, there are occasions when the anesthesiologist is asked to contribute his/her opinion whether a specific high-risk patient will tolerate a specific surgical procedure. This may occur preoperatively but also occurs intraoperatively when the surgical findings suggest that a planned procedure, such as a lobectomy, may require a larger resection such as a pneumonectomy. For these reasons, it is imperative that the anesthesiologist have a complete preoperative knowledge of the patient's medical status and also an appreciation of the pathophysiology of lung resection surgery. There has been a comparatively small volume of research on the short-term (<6 weeks) outcome of these patients. However, this research area is currently very active, and there are several studies which can be used to guide anesthetic management in the perioperative period where it has an influence on outcome.

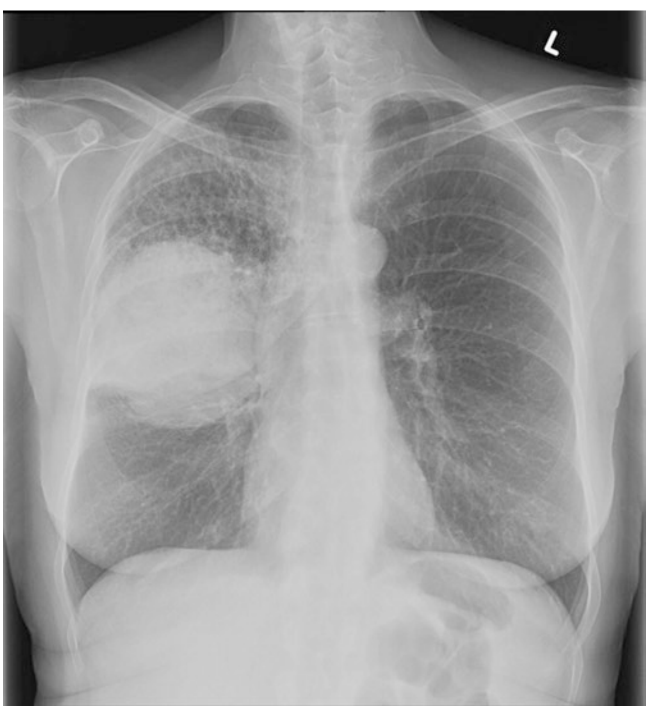

Fig. 2.1 Chest X-ray of a patient with a carcinoma of the right upper lobe scheduled for possible lobectomy or pneumonectomy. The purpose of the preoperative anesthetic assessment of this patient is to stratify the patient's risk and to identify factors which can be managed to improve the perioperative outcome

Thoracic surgeons are now being trained to perform "lung-sparing" resections such as sleeve lobectomies or segmentectomies and to perform resections with minimally invasive techniques such as video-assisted thoracoscopic surgery (VATS) and robotic surgery. The postoperative preservation of respiratory function has been shown to be proportional to the amount of the functioning lung parenchyma preserved. To assess patients with limited pulmonary function, the anesthesiologist must appreciate these newer surgical options in addition to the conventional open lobectomy or pneumonectomy.

Pre-thoracotomy assessment naturally involves all of the factors of a complete anesthetic assessment: past history, allergies, medications, upper airway, etc. This chapter will concentrate on the additional information, beyond a standard anesthetic assessment, that the anesthesiologist needs to manage a thoracic surgical patient. Practice patterns in anesthesia have evolved such that a patient is commonly assessed initially in an outpatient clinic and often not by the member of the anesthesia staff who will actually administer the anesthesia. The actual contact with the responsible anesthesiologist may be only 10–15 min prior to induction. It is necessary to organize and standardize the approach to preoperative evaluation for these patients into two temporally disjoint phases: the initial (clinic) assessment and the final (day-of-admission) assessment. There are elements vital to each assessment which will be described.

Assessment of Respiratory Function

The major cause of perioperative morbidity and mortality in the thoracic surgical population is respiratory complications. Major respiratory complications such as atelectasis, pneumonia, and respiratory failure occur in 15–20% of patients and account for the majority of the expected 3–4% mortality [2]. Cardiac complications such as arrhythmia, ischemia, etc. occur in 10–15% of the thoracic population. Postoperative outcomes after lobectomy are listed in Table 2.1 [3]. The primary focus for the anesthesiologist is to assess the risk of postoperative pulmonary complications.

Table 2.1 Post-lobectomy complications

	Thoracoscopy	Thoracotomy	p value
n	10,173	30,886	
Mortality	1.6%	2.3%	0.06
Length of stay	5 (3–8)	7 (5–9)	<0.001
Any complication	46.5%	50.4%	0.003
Pneumonia	7.3%	8.2%	0.17
Empyema	0.8%	1.4%	0.007
Supraventricular arrhythmia	13.7%	17.9%	<0.0001
Pulmonary embolus	0.6%	1.0%	0.018
Myocardial infarction	0.3%	0.7%	0.01

Based on data from the Nationwide Inpatient Sample Database, Paul et al. [3]

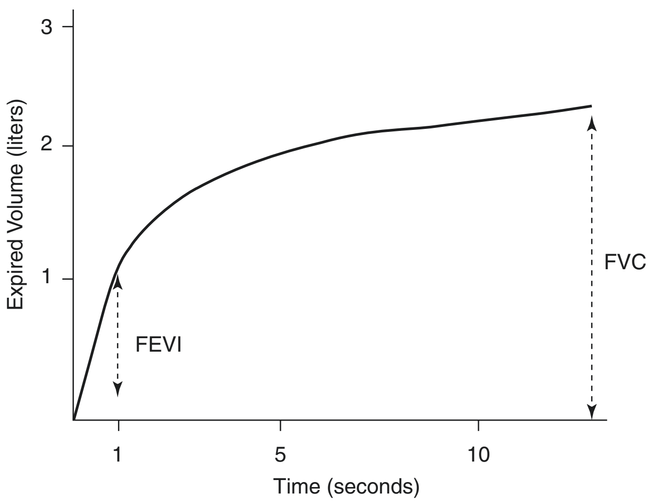

Fig. 2.2 Spirometry should be performed in all pulmonary resection patients to assess the forced expiratory volume in 1 second (FEV1) which can then be corrected for the patient's age, sex, and height to give a percentage of the normal predicted value (FEV1%)

The best assessment of respiratory function comes from a detailed history of the patient's quality of life. All pulmonary resection patients should have baseline simple spirometry preoperatively to measure forced expiratory volume in 1 second (FEV1) and forced vital capacity (FVC) (Fig. 2.2) [4]. Simple portable spirometers are available that can be used easily in the clinic or at the bedside to make these measurements (Fig. 2.3). Objective measures of pulmonary function are required to guide anesthetic management and to have this information in a format that can be easily transmitted between members of the healthcare team. Much effort has been spent to try and find a single test of respiratory function that has sufficient sensitivity and specificity to predict outcome for all pulmonary resection patients. It is now clear that no single test will ever accomplish this. It is useful to assess each patient's respiratory function in three related but largely independent areas: respiratory mechanics, pulmonary parenchymal function, and cardiorespiratory interaction.

Fig. 2.3 An example of a portable handheld spirometer which can be easily used in the preoperative assessment clinic or at the bedside to measure forced expiratory flows and volumes

These can be remembered as the basic functional units of extracellular respiration, which are to get atmospheric oxygen (1) into the alveoli, (2) into the blood, and (3) to the tissues (the process is reversed for carbon dioxide removal).

Lung Mechanical Function

Many tests of respiratory mechanics and volumes show correlation with post-thoracotomy outcome: forced expiratory volume in 1 second (FEV1), forced vital capacity (FVC), maximal voluntary ventilation (MVV), and residual volume/total lung capacity (RV/TLC) ratio. For preoperative assessment, these values should always be expressed as a percent of predicted volumes corrected for age, sex, and height (e.g., FEV1%). Of these the most valid single test for post-thoracotomy respiratory complications is the predicted postoperative FEV1 (ppoFEV1%) [5] which is calculated as:

$$\text{ppoFEV1\%} = \text{preoperative FEV1\%} \times \left(1 - \text{\%functional lung tissue removed}/100\right)$$

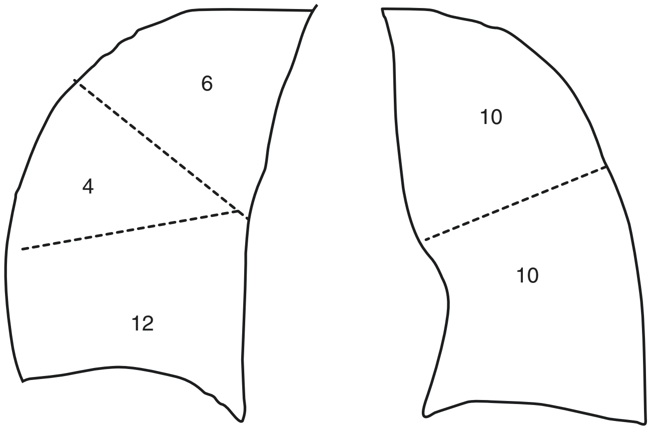

Fig. 2.4 The number of subsegments of each lobe is used to calculate the predicted postoperative (ppo) pulmonary function. For example, following a right lower lobectomy, a patient with a preoperative FEV1 (or DLCO) 70% of normal would be expected to have a ppoFEV1 = 70% × (1–29/100) = 50%

One method of estimating the percent of functional lung tissue is based on a calculation of the number of functioning subsegments of the lung removed (Fig. 2.4). Nakahara et al. [4] found that patients with a ppoFEV1 > 40% had no or minor post-resection respiratory complications. Major respiratory complications were only seen in the subgroup with ppoFEV1 < 40% (although not all patients in this subgroup developed respiratory complications), and 10/10 patients with $ppoFEV_1 < 30\%$ required postoperative mechanical ventilatory support. These key threshold ppoFEV1 values 40% and 30% are extremely useful to remember when managing these patients. The schema of Fig. 2.4 may be overly complicated, and it can be useful just to simply consider the right upper and middle lobes combined as being approximately equivalent to each of the other three lobes with the right lung 10% larger than the left. These data of Nakahara are from work done in the 1980s, and recent advances, such as improved postoperative analgesia, have decreased the incidence of complications in the high-risk (ppoFEV1 < 30%) group [6]. The use of minimally invasive thoracic surgery has also allowed safe pulmonary resection to be performed in individuals traditionally considered to have increased risk [7].

However, a ppoFEV1 value of ≤40% remains useful as a reference point for the anesthesiologist to identify the patient at increased risk. The ppoFEV1 is the most significant independent predictor of complications among a variety of historical, physical, and laboratory tests for these patients. In the 30 years since the original publication by Nakahara, repeated trials in different populations have consistently supported the use of ppoFEV1 < 40% as a threshold for increased risk and ppoFEV1 < 30% as the threshold for high risk [8].

Patients with ppoFEV1 values <40% can be operated on with acceptable morbidity and mortality in certain circumstances. Linden et al. [9] reported on a series of 100 patients with ppoFEV1 < 35% who had lung resections for cancer with only 1 mortality and with a 36% complication rate. Whenever possible, these patients had VATS procedures and thoracic epidural analgesia. The authors propose an absolute lower limit of acceptability for resection as a ppoFEV1 < 20%. It should be appreciated that this report is from a center with a very high volume of thoracic surgery and surgical outcomes for lung cancer are correlated to the volume of surgery. High-volume hospitals had complication and mortality rates (20% and 3%, respectively) that were approximately one-half of low-volume hospitals (44% and 6%) [10]. However, the majority of institutions currently perform VATS procedures without thoracic epidural analgesia.

The actual measured postoperative FEV1 will not be the same as the ppoFEV1 for several reasons. First, it is impossible to predict the actual intraoperative surgical trauma to the chest wall and residual lung segments. Most patients will have FEV1 values immediately postoperatively that are less than the ppoFEV1, and these will improve over a period of 6 months [11]. Second, emphysematous patients will tend to have a lung-volume reduction effect on the residual lobe(s) and may exceed their ppoFEV1 if a hyperinflated lobe is resected. The actual postoperative FEV1 has been shown to be a better predictor of outcome than the ppoFEV1; however, the actual postoperative FEV1 is not available preoperatively.

Absolute predicted postoperative values for FEV1 were used in the past to assess patients. Absolute limits for ppoFEV1 such as 0.8 L were suggested as the lower limits of acceptability for resection. However, absolute values for pulmonary function tests do not take into consideration the wide variation in the size of patients who present for thoracic surgery. An absolute FEV1 result of 1 L for an 80-year-old male 5 ft. (152 cm) in height is normal (100% of predicted), but an FEV1 of 1 L for a 6 ft. (183 cm) 50-year-old male is severely abnormal (24% predicted). It is important always to consider patients' spirometry results as a percentage of their predicted normal.

Patients at increased risk of respiratory complications (ppoFEV1 < 40%) should have complete pulmonary function testing in a pulmonary function laboratory which will include an assessment of lung volumes and airway resistance (Fig. 2.5). These are more sensitive than an examination of the FEV1/FVC ratio to distinguish between obstructive and restrictive lung pathologies and will confirm the clinical

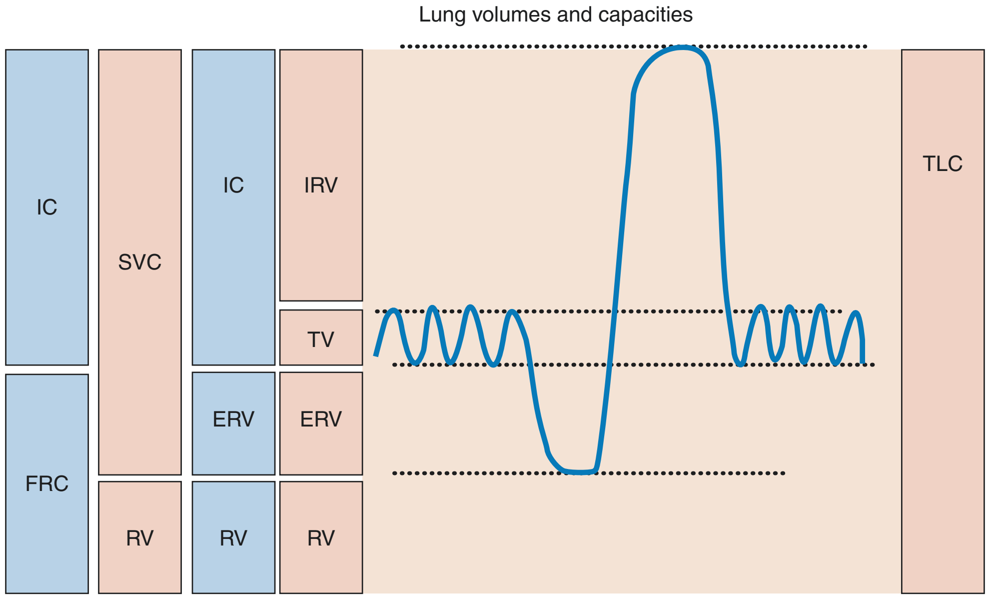

Fig. 2.5 Complete pulmonary function testing will provide data on lung volumes and capacities to differentiate obstructive from restrictive diseases. FRC = functional residual capacity; IC = inspiratory capacity; RV = residual volume; SVC = slow vital capacity; ERV = expiratory reserve volume; TV = tidal volume; IRV = inspiratory reserve volume; TLC = total lung capacity. Measuring closing volume and closing capacity requires insoluble gas washout techniques and is not included in routine pulmonary function testing. However, an appreciation of the variable relationship between closing capacity and FRC and the effects of anesthesia on FRC is essential for the anesthesiologist to understand the changes in gas exchange that occur during anesthesia (the reader is referred to Lumb AB, Nunn's Applied Respiratory Physiology, 7th ed., p. 58, Churchill Livingston Elsevier, Philadelphia, 2010, for a detailed explanation)

diagnosis of the underlying lung disease. Also this permits for optimization of intraoperative management during both two-lung and one-lung ventilation by individualization of settings for mechanical ventilation depending on the lung pathology [12]. There are two basic methods of measurement of lung volumes: insoluble gas dilution and plethysmography (Fig. 2.6). Plethysmography is the common method used in pulmonary function laboratories to measure lung volumes and has largely replaced insoluble gas dilution techniques. The difference (plethysmography-dilution) in measured lung volumes between the two techniques can be used to estimate the volume of bullae in the lung. Previously, maximal breathing capacity was also used to assess patients for pulmonary resection. This simple test was used in the era of pulmonary resection for tuberculosis and has been replaced by modern spirometry.

Pulmonary Parenchymal Function

As important to the process of respiration as the mechanical delivery of air to the distal airways is the subsequent ability of the lung to exchange oxygen and carbon dioxide between the pulmonary vascular bed and the alveoli. Traditionally arterial blood gas data such as PaO_2 < 60 mmHg or $PaCO_2$ > 45 mmHg have been used as cutoff values for pulmonary resection. Cancer resections have now been successfully done or even combined with volume reduction in patients who do not meet these criteria, although they remain useful as warning indicators of increased risk. The most useful test of the gas exchange capacity of the lung is the diffusing capacity for carbon monoxide (DLCO). The DLCO is a reflection of the total functioning surface area of alveolar-capillary interface. This simple noninvasive test which is included with spirometry and plethysmography by most pulmonary function laboratories is a useful predictor of perioperative morbidity and mortality [13]. The corrected DLCO can be used to calculate a post-resection (ppo) value using the same calculation as for the FEV1 (Fig. 2.7). A ppoDLCO <40% predicted correlates with both increased respiratory and cardiac complications and is, to a large degree, independent of the FEV1. The National Emphysema Treatment Trial has shown that patients with a preoperative FEV_1 or DLCO <20% had an unacceptably high perioperative mortality rate [14]. These can be considered as the absolute minimal values compatible with successful outcome. Complete pulmonary function testing, as performed in a pulmonary function laboratory, generates a report with

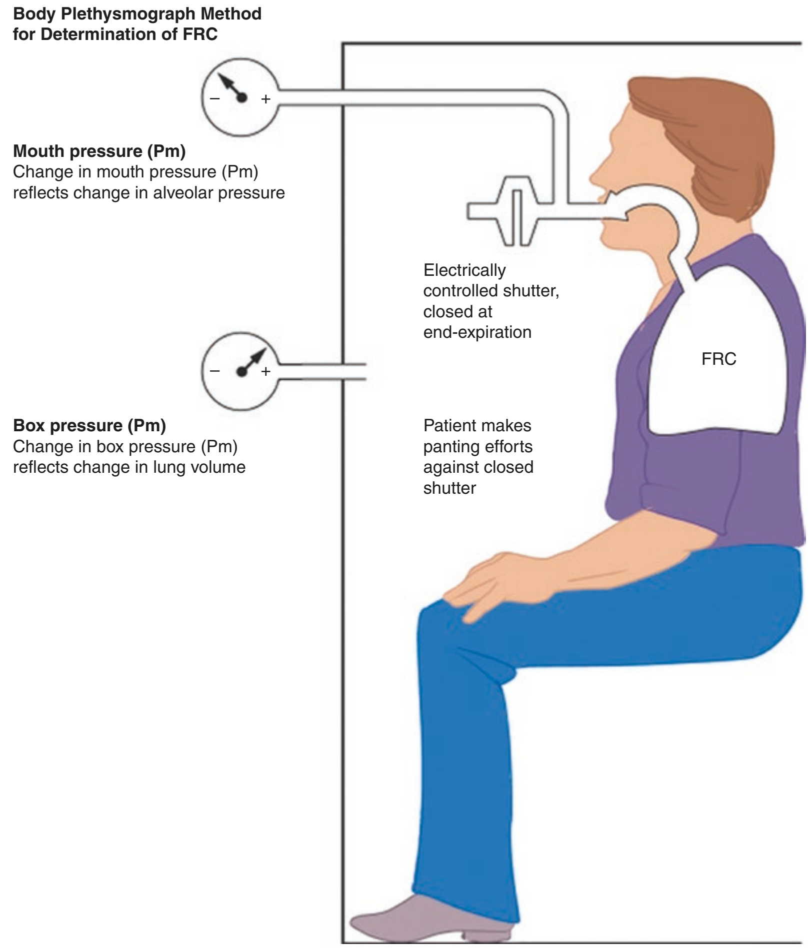

Fig. 2.6 Measurement of lung volumes is commonly performed with whole-body plethysmography with the patient seated in an airtight box. Lung volumes can be calculated from changes in the airway and box pressure since the volume of the box is known

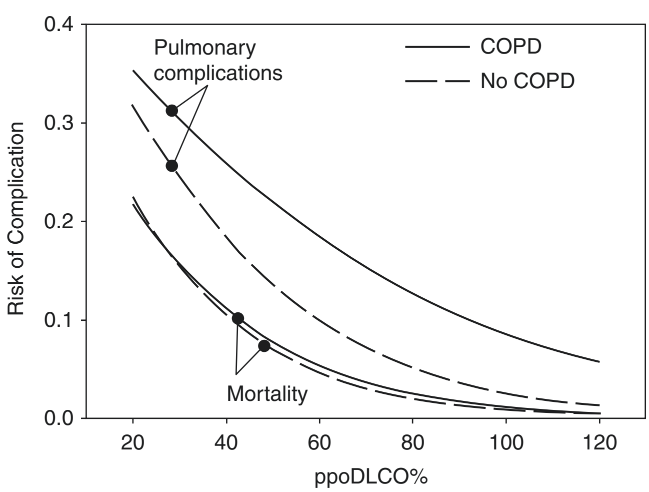

Fig. 2.7 Regression lines for the risk of pulmonary (upper lines) or fatal (lower lines) complications vs. predicted postoperative diffusing capacity for carbon monoxide (ppoDLCO%) following lung resection in patients with (solid lines) and without (dashed lines) chronic obstructive pulmonary disease (COPD). Note that both morbidity and mortality increase sharply when the ppoDLCO falls below a threshold value of 40%. (Reprinted from Ferguson and Vigneswaran [12] with permission)

often >12 test results (Fig. 2.8). Of these results, the two most valid tests for the anesthesiologist to use to assess perioperative risk are the % predicted FEV1 and DLCO. In evaluating a patient for pulmonary resection, the lower of the two values (ppoFEV1 or ppoDLCO) should be used as the guide for risk evaluation [15].

Cardiopulmonary Interaction

The final and perhaps most important assessment of respiratory function is an assessment of the cardiopulmonary interaction. Formal laboratory exercise testing is currently the "gold standard" for assessment of cardiopulmonary function [16], and the maximal oxygen consumption (VO_2 max) is the most useful predictor of post-thoracotomy outcome. The test is performed on a bicycle ergometer or treadmill. Resting measurements are made for 3–5 min. Three minutes of unloaded cycling is performed as a warm-up period. The workload is incremented at a rate designed to allow reaching maximum work capacity in 8–12 min. The test continues to

Test Performed			Pre BD		Post BD	
		Pred.val	Obs.	%Pred.val.	Obs.	%Pred.val.
Total Lung Capacity	(TLC), L	4.2	**7.4**	**175**	----	----
Functional Residual Capacity	(FRC), L	2.6	**6.2**	**239**	----	----
Inspiratory Capacity	(IC), L	1.6	**1.2**	**74**	----	----
Vital Capacity	(VC), L	2.4	**1.5**	**63**	----	----
Residual Volume	(RV), L	1.8	**5.9**	**322**	----	----
RV/TLC Ratio	(RV/TLC), %	43	**80**	**184**	----	----
Forced Vital Capacity	(FVC), L	2.4	**1.5**	**62**	----	----
Forced Exp. Volume In 1 sec.	(FEV1), L	1.7	**0.6**	**34**	----	----
FEV1/FVC Ratio	(FEV1/FVC), %	71	**39**	**55**	----	----
Max. Exp. Flow @ 50% VC	(V50), L/sec	2.4	**0.17**	**7**	----	----
Max. Exp. Flow @ 25% VC	(V25), L/sec	1.2	**0.07**	**6**	----	----
Mid Expiratory Flow 25-75%	(FEF 25–75), L/sec	2.0	**0.2**	**12**	----	----
Airway Resistance	(Raw), cmH2O/L/sec	0.7	2.5	387		
Max. Voluntary Ventilation	(MVV), L/min	50	----	----		
Lung Diffusion Capacity	(DLco), ml/min/mmHg	12.6	7.5	59	*Normal limits: 75–125%*	
VA @ BTPS from DLco	(VA@BTPS), L	4.2	**2.5**	**60**		

NOTE: %Pred. values are BOLD when outside of normal limits. (All except Raw & DLco values.)

Fig. 2.8 A copy of the pulmonary function laboratory test report for a patient with severe emphysema. Of the 15 different results in this report, the 2 results highlighted are the % predicted FEV1 and DLCO, which are the most useful tests for the anesthesiologist assessing a patient for possible pulmonary resection. This patient had taken a bronchodilator immediately before the test so the usual post-bronchodilator (Post BD) test was not repeated. Pred. val. = predicted value corrected for the patient's age, sex, and height. Obs. = patient's measured result. VA = the single-breath dilutional estimate of TLC from the DLCO

a point of symptom limitation (e.g., severe dyspnea) or discontinuation by medical staff (e.g., significant ECG abnormalities) or achievement of maximum predicted heart rate. Estimated VO_2 max is based on the patient's age, sex, and height. For sedentary males, estimated VO_2 max (ml/min) = (height [cm] – age [y]) × 20, i.e., for a 50-year-old male, height 170 cm, and weight 70 kg, the predicted VO_2 max = [(170–50) × 20]/70 = 34 ml/kg/min. For a sedentary woman, age 50, 160 cm, and 60 kg, estimated VO_2 max = [(160–50) × 14]/60 = 26 ml/kg/min (for comparison: the highest VO_2 max recorded in an exercise laboratory is 85 ml/kg/min by the American cyclist Lance Armstrong in 2005 [17]).

The risk of morbidity and mortality is unacceptably high if the preoperative VO_2 max is <15 ml/kg/min [18]. Few patients with a VO_2 max >20 ml/kg/min have respiratory complications. Exercise testing is particularly useful to differentiate between patients who have poor exercise tolerance due to respiratory and cardiac etiologies (Fig. 2.9). The anaerobic threshold measured during exercise testing has also been suggested as a predictor of postoperative complications [19]. The anaerobic threshold is the exercise level at which lactate begins to accumulate in the blood and anaerobic metabolism begins. The anaerobic threshold is approximately 55% of VO_2 max in untrained individuals but rises to >80% in trained athletes. The anaerobic threshold can be documented by repeated blood lactate analysis during exercise or by a threshold increase in CO_2 production above the initial respiratory quotient (ratio of CO_2 production to O_2 consumption, commonly approximately 0.8). A threshold value for AT of <11 ml/kg/min has been suggested as a marker for increased risk, but this has not been well validated [20]. Like FEV1 and DLCO, the VO_2 can be corrected for predicted values. A VO_2 max <60% predicted has been suggested as a threshold for increased risk; however, the % predicted VO_2 max has not been shown to be more useful than the absolute value of VO_2 max as a predictor postoperative of outcomes [21].

Complete laboratory exercise testing is time-consuming and thus expensive. It is generally not cost-effective to use as

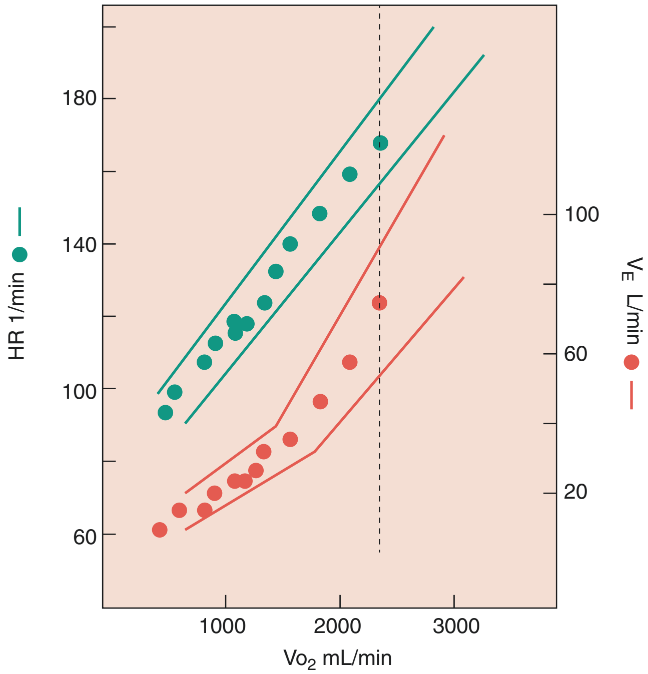

Fig. 2.9 A normal cardiopulmonary exercise test result. As the patient exercises, the increase in oxygen consumption (horizontal axis) is plotted against the heart rate (green dots, left vertical axis) and the minute ventilation (V_E, orange dots, right vertical axis). Normal responses for heart rate and ventilation lie within the green and orange lines. The vertical dashed line is the predicted upper limit of normal based on age. Patients with primarily cardiac causes for exercise limitation will show an excessive increase in heart rate with exercise. Patients with primarily respiratory limitation will show a disproportionate increase in ventilation. Patients with pulmonary vascular disease will have both abnormal heart rate and ventilation responses. (Reprinted with permission from Pearson GF, Thoracic Surgery 3rd. Ed. 2008, Elsevier, Philadelphia, PA)

a routine part of the preoperative assessment for all pulmonary resection patients. Several alternatives have been demonstrated to be valid surrogate tests for pre-thoracotomy assessment. The distance that a patient can walk during a 6-minute walk test (6MWT) shows an excellent correlation with VO_2 max and requires little or no laboratory equipment (Fig. 2.10). For patients with moderate or severe COPD, the 6MWT distance can be used to estimate the VO_2 max by dividing by a figure of 30 (i.e., 600-m distance is equivalent to a VO_2 max of 600/30 = 20 ml/kg/min) [22].

The 6MWT has become the most valid low-tech assessment of exercise capacity [23]. In a series of lobectomy patients, those with a preoperative 6MWT <500 m (approximate VO_2 max = 17 ml/kg) had a significantly higher rate of postoperative complications (61% vs. 37%) compared to those with a 6MWT >500 m [24].

Some centers also assess the fall in oximetry (SpO_2) during exercise. Patients with a decrease of SpO_2 > 4% during exercise (stair climbing 2 or 3 flights or equivalent) [25] are at increased risk of morbidity and mortality. Post-resection exercise capacity can also be estimated based on the amount of functioning lung tissue removed (see Fig. 2.4). An estimated ppoVO_2 max <10 ml/kg/min can be considered a contraindication to pulmonary resection. In a small series [26], mortality was 100% (3/3) patients with a ppoVO_2 max <10 ml/kg/min.

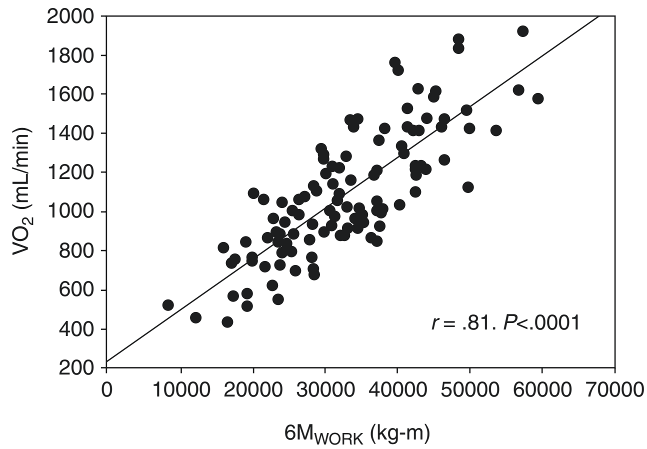

Fig. 2.10 The maximal oxygen consumption VO_2 (ml/min) shows a strong correlation with work ($6M_{WORK}$) for patients with moderate or severe COPD during a 6 min walk test. Work = distance traveled × weight (kg.m). A 70 kg patient who walks 450 m does 31,500 kg.m of work which correlates with an estimated VO_2 max of 1100 ml/min (or 16 ml/kg/min). A simple estimate of the VO_2 max can be made by diving the 6 min walk distance by 30 (i.e., 450 m/30 = 15 ml/kg/min). (Reprinted with permission from Carter et al. [21])

The traditional, and still useful, test in ambulatory patients is stair climbing [27]. Stair climbing is done at the patient's own pace but without stopping and is usually documented as a certain number of flights. There is no exact definition for a "flight," but 20 steps at 6 in./step is a frequent value. The ability to climb five flights correlates with a VO_2 max >20 ml/kg/min, and climbing two flights corresponds to a maximal oxygen consumption (VO_2 max) of 12 ml/kg/min. A patient unable to climb two flights is extremely high risk [28].

After pulmonary resection, there is a degree of right ventricular dysfunction that seems to be in proportion to the amount of functioning pulmonary vascular bed removed. The exact etiology and duration of this dysfunction remain unknown. Clinical evidence of this hemodynamic problem is minimal when the patient is at rest but is dramatic when the patient exercises leading to elevation of pulmonary vascular pressures, limitation of cardiac output, and absence of the normal decrease in pulmonary vascular resistance usually seen with exertion [29].

Regional Lung Function

Prediction of post-resection pulmonary function can be further refined by assessment of the preoperative contribution of the lung or lobe to be resected by imaging of regional lung function [30]. If the lung region to be resected is nonfunctioning or minimally functioning, the prediction of postoperative function can be modified accordingly. This is particularly useful in pneumonectomy patients [31], and regional lung function imaging should be ordered for any potential pneumonectomy patient who has a preoperative FEV1 and/or DLCO <80% (i.e., if ppo values <40% predicted). Regional lung function imaging can be performed by three techniques: radionuclide ventilation/perfusion (V/Q) lung scanning, pulmonary quantitative CT scanning, or three-dimensional dynamic perfusion magnetic resonance imaging (MRI).

Ventilation/perfusion lung scanning is the gold standard. Regional ventilation is assessed by scanning after inhalation of a radiolabeled insoluble gas (commonly xenon-133). Regional lung perfusion is assessed by scanning after intravenous injection of radiolabeled particles that are trapped in the pulmonary capillaries (commonly technetium-99 m macroaggregated albumin) (Fig. 2.11). Actual postoperative lung function has shown a high correlation with predicted values based on preoperative V/Q scanning for FEV1 (r = 0.92), DLCO (r = 0.90), and VO_2 max (r = 0.85). Prediction is more accurate for post-pneumonectomy vs. post-lobectomy values. If there is a discrepancy between the ventilation and perfusion scan results, it is preferable to use the result which attributes the larger proportion of ventilation or perfusion to the diseased lung to estimate the post-resection pulmonary function.

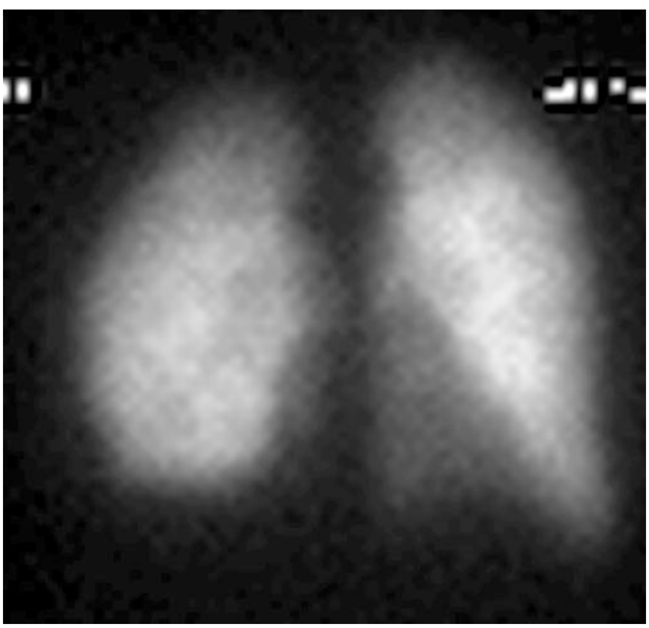

Fig. 2.11 Perfusion scan of a patient with a right lung tumor being assessed for possible pneumonectomy. The perfusion of the right lung (seen on the left in the image) was 37% and the left 63%. Preoperative FEV1 = 74% predicted and DLCO = 70%. Based on the anatomic number of subsegments to be excised, the predicted postoperative (ppo) FEV1 = 74 × 22/42 = 39% and the ppoDLCO = 70 × 22/42 = 37%. Using the regional lung imaging to predict postoperative values, the ppoFEV1 = 74 × 0.63 = 47% and the ppoDLCO = 70 × 0.63 = 44%, which are above the threshold values for increased perioperative risk

Quantitative CT lung scans can be used to estimate post-resection values [32]. Each CT slice is quantified for areas of normal parenchyma, emphysema, and atelectasis. The contribution of each lobe or lung can be estimated based on the volume of normal parenchyma and then used to predict post-operative lung function. Quantitative CT primarily focuses on areas of ventilation and is more accurate for post-lobectomy vs. post-pneumonectomy values. Predicted post-operative values for FEV1 and DLCO were comparable to those derived from V/Q scans but less accurate for VO_2 max. This is a newer technique than V/Q scanning and requires specific imaging expertise. However, due to the routine pre-operative CT scanning of most pulmonary resection patients, it may become more available.

Dynamic MRI uses estimates of regional pulmonary blood volume to assess regional blood flow [33]. This is the newest of the three techniques and is not widely used. It has shown a high level of correlation between predicted and actual values for postoperative FEV1. It has not been assessed for predicting DLCO or VO_2 max.

Split-Lung Function Studies

A variety of methods have been described to try and simulate the postoperative respiratory situation by preoperative unilateral exclusion of a lung or lobe with a double-lumen tube or bronchial blocker and/or by pulmonary artery balloon occlusion of a lung or lobe artery [34]. These tests have not shown sufficient predictive validity for universal adoption in lung resection patients. Lewis et al. [35] have shown that in a group of patients with COPD (ppoFEV1 < 40%) undergoing pneumonectomy, there were no significant changes in the pulmonary vascular pressures intraoperatively when the pulmonary artery was clamped but the right ventricular ejection fraction and cardiac output decreased. Echocardiography may offer more useful information than vascular pressure monitoring in these patients [36]. Split-lung function studies have been replaced in most centers by a combined assessment involving spirometry, DLCO, exercise tolerance, and imaging of regional lung function.

Combination of Tests

No single test of respiratory function has shown adequate validity as a sole preoperative assessment. Prior to surgery, an estimate of respiratory function in all three areas, lung mechanics, parenchymal function, and cardiopulmonary interaction, should be made for each patient. These three aspects of pulmonary function form the "three-legged stool" which is the foundation of pre-thoracotomy respiratory testing (Fig. 2.12). The three-legged stool can also be used to guide intra- and postoperative management (Fig. 2.13) and also to alter these plans when intraoperative surgical factors necessitate that a resection becomes more extensive than foreseen. If a patient has a ppoFEV1 > 40%, it should be possible for that patient to be extubated in the operating room at the conclusion of surgery assuming the patient is alert, warm, and comfortable ("AWaC"). Patients with a ppoFEV1 < 40% will usually comprise about one-fourth of an average thoracic surgical population. If the ppoFEV1 is >30% and exercise tolerance and lung parenchymal function exceed the increased risk thresholds, then extubation in the operating room should be possible depending on the status of associated medical conditions. Those patients in this subgroup who do not meet the minimal criteria for cardiopulmonary and parenchymal function should be considered for staged weaning from mechanical ventilation postoperatively so that the effect of the increased oxygen consumption of spontaneous ventilation can be assessed. Patients with a ppoFEV1 20–30% and favorable predicted cardiorespiratory and parenchymal function can be considered for early extubation if thoracic epidural analgesia is used or if the resection is performed with VATS. Otherwise, these patients should have a postoperative staged weaning from mechanical ventilation. In the borderline group (ppoFEV1 30–40%), the presence of several associated factors and diseases which should be documented during the preoperative assessment will enter into the considerations for postoperative management (see below).

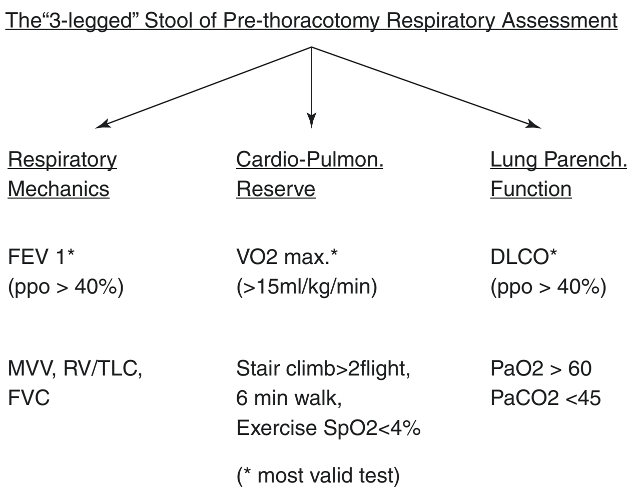

Fig. 2.12 The "three-legged stool" of pre-thoracotomy respiratory assessment involves evaluation of lung mechanical function, pulmonary parenchymal function, and cardiopulmonary interaction for each patient. The most valid test in each area is denoted by *. The threshold values below which risk increases are in parentheses. Ppo = predicted postoperative value as a % of the patient's normal value

Jordan and Evans have outlined a protocol for planned elective admission of pulmonary resection patients to the intensive care unit postoperatively [37]. In their scheme, patients age ≥ 70 years or with fibrotic lung disease or with positive cardiovascular risk assessment or with an elevated ASA score or poor lung function (preoperative FEV <47%) would be admitted to ICU. Others would go to the recovery unit and then a monitored ward bed.

Concomitant Medical Conditions

Cardiac Disease

Cardiac complications are the second most common cause of perioperative morbidity and mortality in the thoracic surgical population. The commonest major cardiac complications are myocardial ischemia/infarction, arrhythmias, and heart failure. Several schemes have been developed to predict overall perioperative cardiac risk (see Table 2.2). The revised cardiac risk score [38] was developed for all major noncardiac sur-

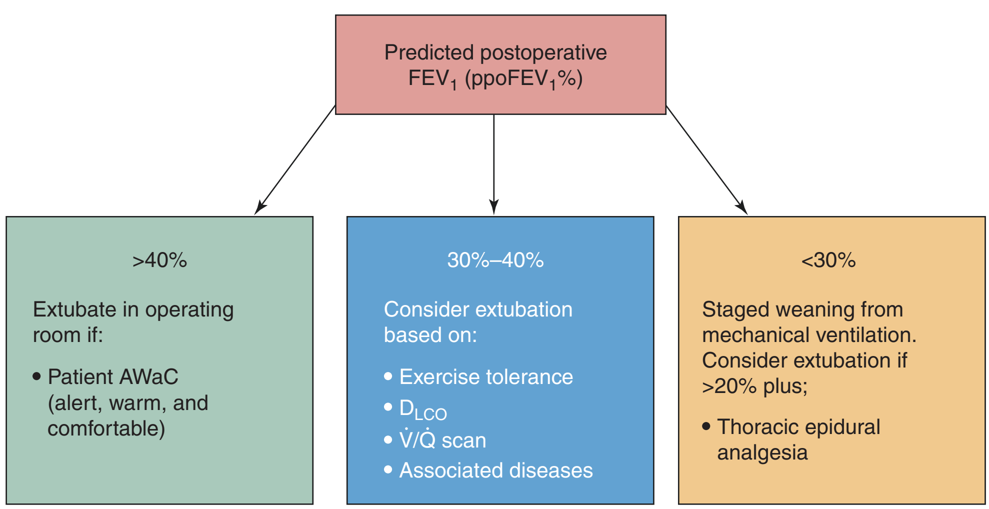

Fig. 2.13 Anesthetic management guided by preoperative assessment and the amount of functioning lung tissue removed during surgery

gery, and the thoracic revised cardiac risk score was developed specifically for thoracic surgery patients [39]. However, the predictive ability of these two scores in prospective studies has not always been high [40]. There is always a delay of several years between the time of development of these risk indices and actual prospective clinical studies. Their lack of accuracy in prospective studies may be due in part to the evolving underlying characteristics of the population with cardiac disease and also due to the rapid progress in preventing and treating major cardiovascular complications. Patients being treated with angiotensin-converting enzyme inhibitors or angiotensin II receptor blockers preoperatively are at an increased risk of postoperative cardiovascular complications if these medications are continued in the 24-h period before surgery [41].

Table 2.2 A comparison of the preoperative revised cardiac risk index and the thoracic revised cardiac risk index

Revised cardiac risk index (RCRI)	Points	Thoracic RCRI	Points
High-risk surgery (all major thoracic surgery)	1	Pneumonectomy	1.5
Coronary artery disease	1	Coronary artery disease	1.5
Congestive heart failure	1		
Cerebrovascular disease	1	Cerebrovascular disease	1.5
Diabetes on insulin	1		
Serum creatinine >2 mg/ml (>177 umol/L)	1	Serum creatinine >2 mg/ml (>177 umol/L)	1

Based on Licker et al. [95]
RCRI: 0–1 point = low-risk mortality (0.8%); 2 points = moderate risk (2.4%); >2 points = high risk (5.4%)
Thoracic RCRI: 0 points = low risk (<5%); 1–1.5 points = moderate risk (5–10%); ≥2 points = high risk (11–20%)

Ischemia

Because the majority of pulmonary resection patients have a smoking history, they already have one risk factor for coronary artery disease (other factors include male sex, heredity, diabetes, obesity, high blood pressure, and elevated cholesterol). Elective pulmonary resection surgery is regarded as an "intermediate-risk" procedure in terms of perioperative cardiac ischemia [42]. The overall documented incidence of post-thoracotomy ischemia is 5% and peaks on days 2–3 postoperatively [43]. Beyond the standard history, physical, and electrocardiogram, further routine testing for cardiac disease does not appear to be cost-effective for all prethoracotomy patients.

The American College of Cardiology and American Heart Association have developed algorithms for preoperative cardiac investigations [44]. These guidelines are inclusive for all patients and not specific to thoracic surgery patients. A simplified algorithm, based on these recommendations, is presented in Fig. 2.14. Patients with intermediate clinical predictors of

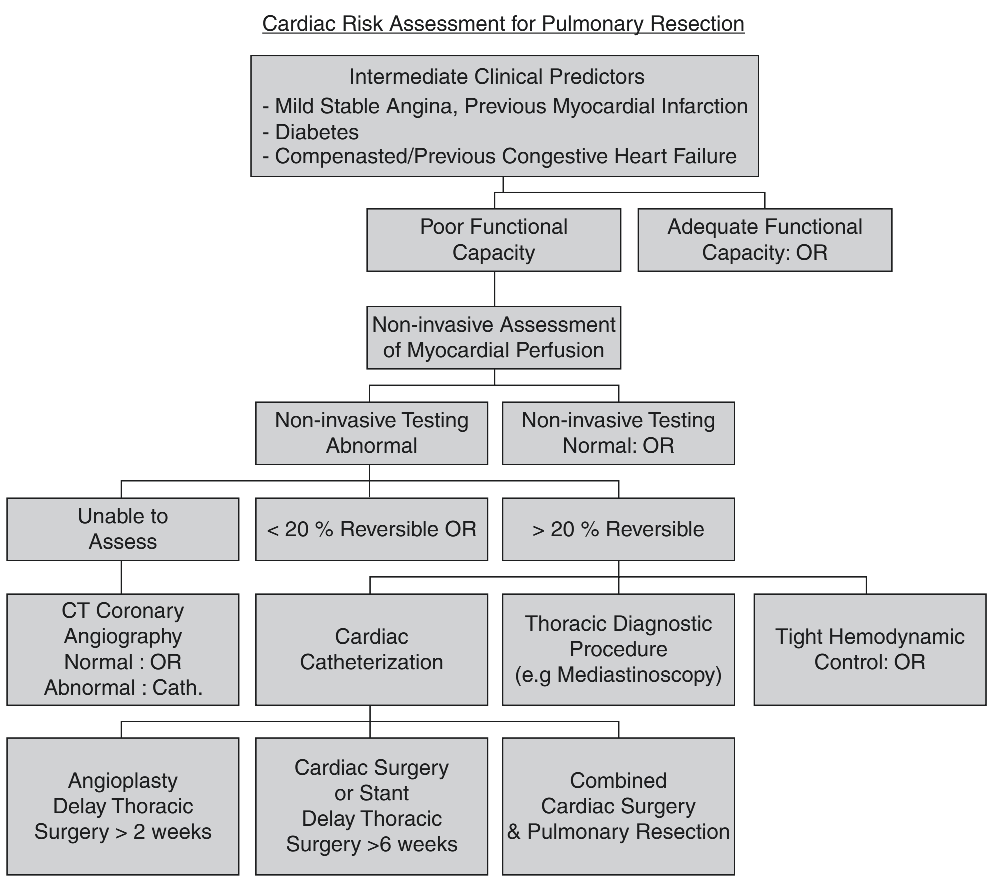

Fig. 2.14 An algorithm for cardiac risk assessment prior to noncardiac thoracic surgery. (Based on Fleisher et al. [43]). OR = operating room (i.e., proceed with surgery without further cardiac investigation). Cath. = coronary catheterization. Once a patient is found to have an abnormal result on noninvasive testing of myocardial perfusion, choosing the optimal pathway becomes complicated and requires a combined consultation with the surgeon, cardiologist, and patient

increased cardiac risk (stable angina, diabetes, etc.) who have adequate functional capacity do not need further cardiac investigation prior to pulmonary surgery. Patients with these intermediate predictors and poor functional capacity should have noninvasive testing of myocardial perfusion at rest and during stress. The estimate of myocardial perfusion can be performed by nuclear medicine (technetium sestamibi or thallium injection) or transthoracic echocardiography at rest and during stress. The stress can be either with exercise or by injection of a coronary vasodilator (dipyridamole) or an inotrope (dobutamine). Based on the results from studies in vascular surgery [45], it can be extrapolated that patients with normal perfusion or who have areas of reversibility in <20% of myocardial segments can proceed to surgery without further cardiac investigation.

For patients who have major reversibility on a myocardial perfusion test, the diagnostic and therapeutic pathway is less clear. The standard recommendation is to proceed to cardiac catheterization. However, in individual circumstances, it could be an option to proceed with a minor diagnostic procedure (such as an endobronchial ultrasound or mediastinoscopy) first if there is a reasonable possibility that the patient may not have a resectable cancer. Or, it may be considered to proceed with the pulmonary resection with very tight perioperative hemodynamic control since it is not clear that coronary intervention improves perioperative outcome in patients who are not clear candidates for intervention outside the perioperative period [46]. The wisdom of elective perioperative β-blockade in these patients is debatable [47]. β-blockade may decrease the perioperative cardiac risk but increase the risk of stroke. Patients who have an indication for β-blockade apart from the perioperative context should be started and continued on these medications perioperatively, appreciating that many thoracic surgical patients have reactive airways disease that may be exacerbated by β-blockade. The use of β-blockers otherwise should be guided by specific hemodynamic indications.

For patients who require coronary catheterization, the results may necessitate angioplasty with or without stenting or coronary artery bypass surgery before or at the same time as pulmonary surgery (see Chap. 40). It is very important that the interventional cardiologist be made aware of the patient's diagnosis and the perioperative context prior to angiography. If bare metal coronary stents are placed, the patient will require dual antiplatelet therapy with a $P2Y_{12}$ receptor antagonist (clopidogrel, prasugrel, or ticagrelor) and aspirin for 4–6 weeks before the $P2Y_{12}$ inhibitor can be stopped (and the aspirin continued) preoperatively [48]. In some cases this is an acceptable delay before a major pulmonary resection or other thoracic surgeries. However, if drug-eluting stents are placed, the risk of stent stenosis, which is often fatal, is unacceptable if dual antiplatelet therapy is discontinued in the first 6 months. This is generally not an acceptable delay for cancer surgery.

Timing of lung resection surgery following a myocardial infarction is always a difficult decision. Limiting the delay to 4–6 weeks in a medically stable and fully investigated and optimized patient seems acceptable after myocardial infarction. The anesthesiologist needs to appreciate that the preoperative assessment and the therapeutic options for patients with significant coronary artery disease presenting for lung surgery are becoming very complicated and no single algorithm can be applied given the complexities of each individual case and the local availability of diagnostic equipment and personnel. Each of these patients needs to be managed by a team consultation that includes the thoracic surgeon, the cardiologist, the anesthesiologist, and the patient and family. The management of a patient who is discovered to have an incidental lung lesion during preoperative assessment for coronary artery or cardiac valvular surgery is discussed in Chap. 40.

Arrhythmias

The management of post-thoracotomy arrhythmias is discussed in Chap. 56. Arrhythmias are a common complication of pulmonary resection surgery, and the incidence is 30–50% of patients in the first week postoperatively when Holter monitoring is used [49]. Of these arrhythmias, 60–70% are atrial fibrillation. Several factors correlate with an increased incidence of arrhythmias; these include extent of lung resection (pneumonectomy 60% vs. lobectomy 40% vs. non-resection thoracotomy 30%), intrapericardial dissection, intraoperative blood loss, and age of the patient. Extrapleural pneumonectomy patients are a particularly high-risk group [50].

Two factors in the early post-thoracotomy period interact to produce atrial arrhythmias.

1. Increased flow resistance through the pulmonary vascular bed due to permanent (lung resection) or transient (atelectasis, hypoxemia) causes, with attendant strain on the right side of the heart.
2. Increased sympathetic stimuli and oxygen requirements, maximal on the second postoperative day as patients begin to mobilize.

In some pneumonectomy patients, the right heart may not be able to increase its output adequately to meet the usual postoperative stress. Transthoracic echocardiographic studies have shown that pneumonectomy patients develop an increase in right ventricular systolic pressure as measured by the tricuspid regurgitation jet (TRJ) on postoperative day 2 but not on day 1. An increase in TRJ velocity has been associated with post-thoracotomy supraventricular tachyarrhythmias [36]. Patients with COPD are more resistant to pharmacologic rate control when they develop post-thoracotomy atrial fibrillation and often require multiple drugs [51].

A wide variety of antiarrhythmics have been tried to decrease the incidence of atrial arrhythmias after lung surgery. The best known of these are digoxin preparations. It has been demonstrated that digoxin does not prevent arrhythmias after pneumonectomy or other intrathoracic procedures. Other agents which have been tried to prevent post-thoracotomy arrhythmias include β-blockers, verapamil, and amiodarone. All of these agents decrease arrhythmias in thoracic patients. At present the consensus statement of the American Association for Thoracic Surgery [52] recommends continuing β-blockers for patients who are already on them and intravenous magnesium for any patient who may have low or depleted serum and/or body stores of magnesium. In patients at high risk of postoperative supraventricular arrhythmias (lobectomy, pneumonectomy, esophagectomy, etc.), consideration of prophylactic therapy with diltiazem or amiodarone should be considered.

In one study [53] patients who subsequently developed atrial tachyarrhythmias could be identified in the early postoperative period by their right ventricular response to the withdrawal of supplemental oxygen. On the first postoperative day, a decrease of FiO_2 from 0.35 to 0.21 caused a significant rise of right ventricular end-diastolic pressure (RVEDP) in the patients who subsequently developed arrhythmias. Thoracic epidural analgesia (TEA) with local anesthetics may decrease the incidence and severity of arrhythmias. This effect is thought to be due to increasing myocardial refractory period, decreasing ventricular diastolic pressures, and improving endocardial/epicardial blood flow ratios [54].

Age

Perioperative management of the geriatric patient for thoracic surgery is discussed in Chap. 32. There is no maximum age that is a cutoff for pulmonary resection surgery. In one series, the operative mortality in a group of patients 80–92 years of age was 3%, a very respectable figure [55]. However, the rate of respiratory complications (40%) was double than expected in a younger population, and the rate of cardiac complications (40%), particularly arrhythmias, was nearly triple than which would be seen in younger patients. Naturally, the long-term (5-year) postoperative survival is decreased in the geriatric population [56].

In the elderly, thoracotomy should be considered a high-risk procedure for cardiac complications, and cardiopulmonary function is the most important part of the preoperative assessment. An algorithm for the cardiac assessment of the geriatric patient for thoracic surgery is presented in Fig. 2.15. Exercise tolerance seems to be the primary determinant of outcome in the elderly [57]. The ACC/AHA guidelines [43] suggest that with adequate functional capacity, patients with "intermediate" predictors of coronary artery disease do not need further cardiac assessment. However, this recommendation should not be extrapolated to elderly patients. The ACC/AHA guidelines define "adequate functional capacity" as four metabolic equivalents (METS). One MET is the basal resting energy output which is commonly equated to an oxygen consumption of 3.5 ml/kg/min. Four METS are the equivalent of climbing one flight of stairs (Table 2.3) which does not represent an adequate level of exercise capacity for a geriatric patient for major pulmonary resection. The elderly should have, as a minimum cardiac investigation, a transthoracic echocardiogram, to rule out pulmonary hypertension. Although the mortality resulting from lobectomy among the elderly is acceptable, the mortality from pneumonectomy,

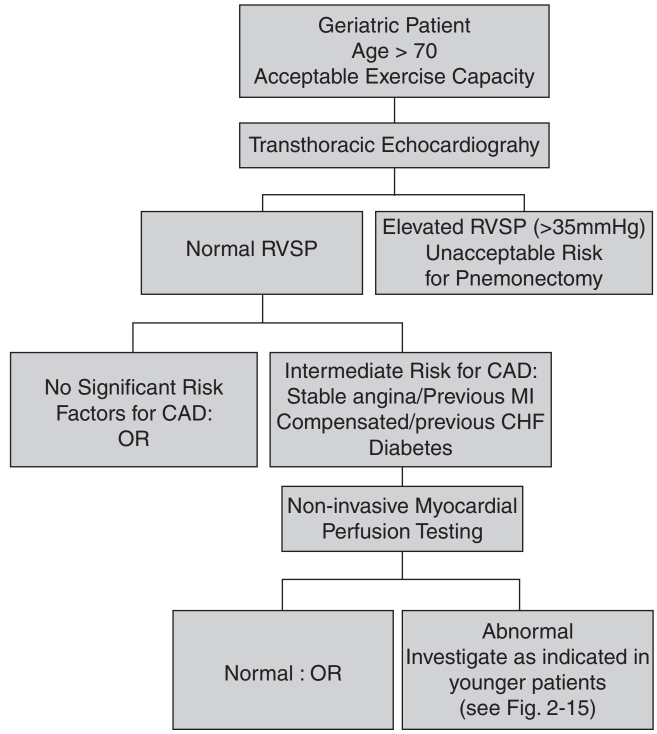

Fig. 2.15 An algorithm for preoperative cardiac investigation in a geriatric patient prior to pulmonary resection surgery. RVSP = right ventricular systolic pressure estimated by echocardiography. CAD = coronary artery disease. OR = operating room (i.e., proceed with surgery without further cardiac investigation)

Table 2.3 Energy consumption in metabolic equivalents (METS) of various activities

Activity	METS
Sitting quietly	1
Walking 1 block	2
Playing the accordion	2
Climbing 1 flight stairs	4
Sexual intercourse[a]	6
Bowling[a]	8
Ice hockey	8
Running 6 mph	10
Cross-country ski racing	14

MET = basal oxygen consumption = 3.5 ml/kg/min. Based on data from Hlatky MA, et al. Am J Cardiol 1989; 64: 651–654; Fleisher et al. [42]
[a]Bowling and sexual intercourse are given fewer METS in some classifications: Ainsworth BA, et al. Med Sci Sports Exerc 1992; 25: 71–80

particularly right pneumonectomy, is excessive [58]. Geriatric patients with intermediate-risk indicators of coronary artery disease should also have noninvasive myocardial perfusion testing. The elderly may benefit from efforts to increase exercise capacity preoperatively. Even a short, 7-day, period of intensive rehabilitation has been shown to increase the 6MWT and decrease pulmonary complications and length of stay in a group of geriatric patients having lung cancer surgery [59].

Renal Dysfunction

Renal dysfunction following pulmonary resection surgery is associated with a high mortality. In 1994, Golledge and Goldstraw [60] reported an incidence of renal impairment after thoracic surgery of 24% with a perioperative mortality of 19% (6/31) in patients who developed a significant elevation of serum creatinine in the post-thoracotomy period, compared to 0% (0/99) in those who did not show any renal dysfunction. Fortunately, a more recent study by Ishikawa et al. has shown that the incidence of postoperative renal injury in thoracic surgery (as defined by the acute kidney injury score) has decreased to 6% and there was no increase in mortality associated with acute kidney injury [61]. Factors associated with an elevated risk of renal impairment were identified in a multivariate analysis by Ahn et al. [62]. (see Table 2.4). Of note, in this study, there was no correlation between intraoperative fluid restriction and postoperative renal dysfunction. Nonsteroidal anti-inflammatory agents (NSAIDs) were not associated with renal impairment in this series but are clearly a concern in any thoracotomy patient with an increased risk of renal dysfunction. The high mortality in pneumonectomy patients from either renal failure or postoperative pulmonary edema emphasizes the importance of fluid management in these patients [63] and the need for close and intensive perioperative monitoring, particularly in those patients on diuretics or with a history of renal dysfunction. The importance of renal dysfunction, either preoperative dialysis or a serum creatinine value >2 mg/dL (>175 umol/L), as a predictor for prolonged length of stay after lobectomy was reconfirmed in an analysis of the Society of Thoracic Surgeons database for the period 2002–2006 [4].

Table 2.4 Factors associated with an increased risk of post-thoracotomy renal impairment

1. Decreased renal function + intraoperative hydroxyethyl starch
2. Preoperative angiotensin-converting enzyme inhibitor/angiotensin receptor blocker therapy
3. Pneumonectomy/esophagectomy
4. Diabetes mellitus
5. Cerebrovascular disease
6. Low serum albumin level

Chronic Obstructive Pulmonary Disease

The most common concurrent illness in the thoracic surgical population is chronic obstructive pulmonary disease (COPD) which incorporates three disorders: emphysema, peripheral airways disease, and chronic bronchitis. Any individual patient may have one or all of these conditions, but the dominant clinical feature is impairment of expiratory airflow [64]. Assessment of the severity of COPD has traditionally been on the basis of the FEV1% of predicted values. The American Thoracic Society categorizes stage I > 50% predicted FEV1% (this category previously included both "mild" and "moderate" COPD), stage II 35–50%, and stage III <35%. Life expectancy may be less than 3 years in stage III patients >60 years of age. Stage I patients should not have significant dyspnea, hypoxemia, or hypercarbia, and other causes should be considered if these are present. A complete discussion of perioperative management of patients with COPD is presented in Chap. 31. Of specific importance in the preoperative assessment of the patient with COPD prior to pulmonary resection is to assess for chronic carbon dioxide retention and to initiate therapy for any potentially treatable complications of COPD.

Carbon Dioxide Retention

Many stage II or III COPD patients have an elevated $PaCO_2$ at rest. It is not possible to differentiate these "CO_2 retainers" from non-retainers on the basis of history, physical examination, or spirometric pulmonary function testing [65]. This CO_2 retention seems to be more related to an inability to maintain the increased work of respiration (W_{resp}) required to keep the $PaCO_2$ normal in patients with mechanically inefficient pulmonary function and not primarily due to an alteration of respiratory control mechanisms. The $PaCO_2$ rises in these patients when a high FiO_2 is administered due to a relative decrease in alveolar ventilation [66] and an increase in alveolar dead space and shunt by the redistribution of perfusion away from lung areas of relatively normal V/Q matching to areas of very low V/Q ratio because regional hypoxic pulmonary vasoconstriction (HPV) is decreased [67] and also due to the Haldane effect [68]. However, supplemental oxygen must be administered to these patients postoperatively to prevent the hypoxemia associated with the unavoidable fall in functional residual capacity (FRC). The attendant rise in $PaCO_2$ should be anticipated and monitored. To identify these patients preoperatively, all stage II or III COPD patients need an arterial blood gas. Also, it is important to know the patient's baseline preoperative $PaCO_2$ to guide weaning if mechanical ventilation becomes necessary in the postoperative period.

Preoperative Therapy of COPD

There are four treatable complications of COPD that must be actively sought and therapy begun at the time of the initial pre-thoracotomy assessment. These are atelectasis, broncho-

Table 2.5 Concurrent problems that should be treated prior to anesthesia in COPD patients

Problem	Method of diagnosis
Bronchospasm	Auscultation
Atelectasis	Chest X-ray
Infection	History, sputum analysis
Pulmonary edema	Auscultation, chest X-ray

spasm, respiratory tract infections, and pulmonary edema (see Table 2.5). Atelectasis impairs local lung lymphocyte and macrophage function predisposing to infection [69]. Pulmonary edema can be very difficult to diagnose by auscultation in the presence of COPD and may present very abnormal radiological distributions (unilateral, upper lobes, etc.) [70]. Bronchial hyper-reactivity may be a symptom of congestive failure [71] or may represent an exacerbation of reversible airway obstruction. All COPD patients should receive maximal bronchodilator therapy as guided by their symptoms. Only 20–25% of COPD patients will respond to corticosteroids. In a patient who is poorly controlled on sympathomimetic and anticholinergic bronchodilators, a trial of corticosteroids may be beneficial [72]. It is not clear if corticosteroids are as beneficial in COPD as they are in asthma; pharmacotherapy for reactive airway diseases is discussed in Chap. 8.

Physiotherapy

Patients with COPD have fewer postoperative pulmonary complications when a perioperative program of intensive chest physiotherapy is initiated preoperatively [73]. Among COPD patients, those with excessive sputum benefit the most from chest physiotherapy. Among the different modalities available (cough and deep breathing, incentive spirometry, PEEP, CPAP, etc.), there is no clearly proven superior method. The important variable is the quantity of time spent with the patient and devoted to chest physiotherapy. Family members or non-physiotherapy hospital staff can easily be trained to perform effective preoperative chest physiotherapy, and this should be arranged at the time of the initial preoperative assessment. Even in the most severe COPD patient, it is possible to improve exercise tolerance with a physiotherapy program. Little improvement is seen before 1 month. In one small study, eight patients who had been refused pulmonary resection on the basis of poor pulmonary function were enrolled in a 4-week program of pulmonary rehabilitation. After the program, the mean 6-min walk test distance for the group increased 29%, and the mean FEV1 increased 5%. All eight patients then had lobectomies without any perioperative mortality [74].

Comprehensive 8–12-week programs of pulmonary rehabilitation involving physiotherapy, exercise, nutrition, and education have been clearly shown to improve functional capacity for patients with severe COPD [75]. These longer programs are generally not an option in resections for malignancy although for nonmalignant resections in severe COPD patients, rehabilitation should be considered. The concept of trying to increase a patient's exercise capacity preoperatively has recently been suggested. In a small randomized controlled trial, Morano et al. [76]. compared standard preoperative chest physiotherapy with pulmonary rehabilitation for a 4-week period before lung resection for cancer in patients with borderline pulmonary function (mean preoperative FEV1 50% predicted). Pulmonary rehabilitation involved 1-h sessions 5 days/week and included periods of interval training to 80% maximal capacity. The 6MWT distance increased significantly in the rehabilitation group (mean 425 to 475 m, $p < 0.05$) vs. no change in the control group, and there was a significant decrease in postoperative morbidity and length of stay (7.8 vs. 12.2 days, $p = 0.04$).

Restrictive Lung Diseases

Restrictive lung physiology is characterized on pulmonary function testing by decreased lung volumes but preserved forced expiratory volume in 1 second to forced vital capacity (FEV1/FVC) ratio. This pattern can be caused by diseases of the lung parenchyma (e.g., interstitial lung diseases), extrinsic problems affecting the pleura or chest wall (e.g., pleural effusions, scoliosis, severe obesity), or disorders causing weakness of the muscles of breathing (e.g., myasthenia gravis, Guillain-Barré syndrome).

Interstitial lung diseases (ILDs) are a heterogeneous group of disorders characterized by inflammation and fibrosis of the lung parenchyma affecting the alveolar-capillary unit. They are usually discerned from other restrictive lung diseases by an impaired diffusion capacity of the lungs for carbon monoxide (DLCO). The most common identifiable causes are related to exposure to occupational or environmental agents (e.g., silica, asbestos), drug-related toxicity (e.g., bleomycin, amiodarone), or radiation-induced lung injury. However, for a significant proportion of patients, a specific cause is never identified. These patients are broadly grouped into the diagnostic category of idiopathic interstitial pneumonia (IIP). There are multiple subcategories of IIP, and unfortunately the terminology has been confusing and overlapping in the literature. Preoperative risk assessment for pulmonary resection in patients with restrictive lung disease should proceed as outlined above with evaluation of ppoFEV1, ppoDLCO, and exercise capacity.

Among the subtypes of IIP, the one which is particularly relevant to the anesthesiologist is idiopathic pulmonary fibrosis (IPF) which is also called usual interstitial pneumonia (UIP). Differentiation of IPF from the other types of IIP is based on a combination of clinical and radiologic findings and may require histologic confirmation [77]. One study of pulmonary resections for non-small cell lung cancer in patients with IIP found significant differences in short- and long-term morbidity and mortality between an IPF group (n = 46) and non-IPF (n = 57) patients. Although other pre- and intraoperative risk factors were equal, the IPF patients tended to have a lower FRC with a preservation of the FEV1/FRC ratio. IPF patients had a higher 30-day mortality (7%) than non-IPF patients (0%) and a lower 5-year survival: 22% vs. 53%. Patients with IPF seem to be particularly at risk for perioperative lung injury during pulmonary resection [78].

Pulmonary Hypertension

A detailed discussion of the management of the patient with pulmonary hypertension for thoracic surgery is presented in Chap. 34. In one series, 19/279 patients having a lobectomy for cancer had pulmonary hypertension (right ventricular systolic pressure >36 mmHg on preoperative transthoracic echocardiography). Although there were trends toward increased morbidity and mortality in the pulmonary hypertension group, they did not reach statistical significance in this small sample. Pulmonary hypertension is not an automatic contraindication to thoracic surgery.

Smoking

Pulmonary complications are decreased in thoracic surgical patients who cease smoking for >4 weeks before surgery [79]. Carboxyhemoglobin concentrations decrease if smoking is stopped >12 h [80]. It is extremely important for patients to avoid smoking postoperatively. Smoking leads to a prolonged period of tissue hypoxemia. Wound tissue oxygen tension correlates with wound healing and resistance to infection. Wound healing is improved in patients who stop smoking >4 weeks preoperatively [81]. There is no rebound increase in pulmonary complications if patients stop for shorter (<8 weeks) periods before surgery [82]. The balance of evidence suggests that thoracic surgical patients should be counseled to stop smoking and advised that the longer the period of cessation, the greater the risk reduction for postoperative pulmonary complications [83]. Levels of successful cessation of smoking can exceed 50% at 1 year with a program of counseling and nicotine replacement [84].

Type of Surgical Procedure

It is important for the anesthesiologist to have an appreciation of the implications of the proposed type and extent of surgical resection. Pneumonectomy is the classic pulmonary resection operation for lung cancer. Prediction of postoperative pulmonary function and risks with a combination of pulmonary function tests and ventilation/perfusion scans, as outlined earlier, is accurate in pneumonectomy patients. Even in geriatric patients, short-term morbidity and mortality are acceptable using these pre-resection prediction criteria [85]. It has been suggested that a preoperative VO_2 max of 20 ml/kg/min should be used as the lower limit for acceptability in pneumonectomy patients [86]. However, it is now appreciated that many patients do not have an acceptable quality of life after a pneumonectomy [87]. Because of this, surgeons are more likely to use lung-sparing procedures such as a bi-lobectomy or bronchial-sleeve lobectomy whenever possible to avoid a pneumonectomy. The frequency of pneumonectomies as a percentage of all lung cancer operations has decreased in the past 20 years from approximately 20% to 5% [88].

A bi-lobectomy is a useful alternative procedure to a right pneumonectomy when surgically possible. The complication rate following bi-lobectomies is intermediate between that for lobectomies and pneumonectomies and lower for upper bi-lobectomies than lower bi-lobectomies [89]. A nonanatomic wedge resection of a lung cancer is also a possibility in high-risk cases. Although the cure rate is less than an anatomical resection, there is a lower short-term morbidity and mortality in high-risk cases [90].

Minimally invasive video-assisted thoracoscopic surgery (VATS) or robotic surgeries are rapidly becoming the commonest approaches for a majority of pulmonary resections. There is a general consensus that patients have fewer complications and less postoperative pain when comparable resections are performed by VATS than by open thoracotomy [91]. Increased-risk patients with a ppoFEV1 or ppoDLCO <40% seem to have a significantly lower morbidity and mortality after lobectomy via VATS vs. thoracotomy [92]. A non-randomized comparison of matched patients having lobectomies via thoracotomy (n = 167) or VATS (n = 173) suggested that the threshold for increased risk could be shifted down from a ppoFEV1 of 40% in the thoracotomy patients to 30% in the VATS patients (see Fig. 2.16) [93]. It was not possible to identify a lower threshold of ppoDLCO for complications after VATS lobectomy (see Fig. 2.17); however, there were very few patients with a ppoDLCO <40% in this population.

Combined Strategies for Preoperative Assessment

Several multisystemic schemes to assess perioperative risk and guide preoperative evaluation have been developed. The American College of Surgeons has developed an online risk calculator based on the National Surgical Quality Improvement Program (NSQIP) database [94] (http://riskcalculator.facs.org/RiskCalculator). This calculator includes 21 preoperative factors (demographics, comorbidities, and procedure). It allows for individualized estimation of risks of

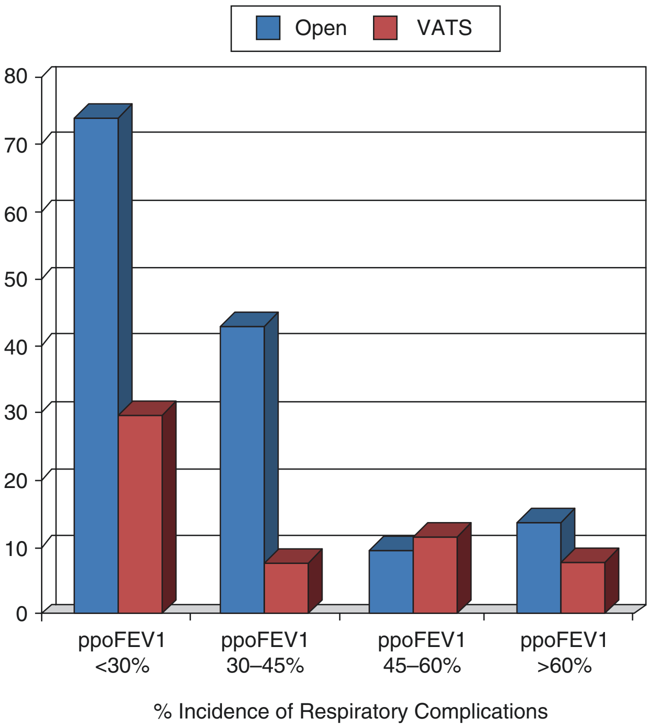

Fig. 2.16 A comparison of the incidence of postoperative respiratory complications after open (thoracotomy) vs. VATS lobectomies for lung cancer. ppo = predicted postoperative value. FEV1 = forced expiratory volume in 1 second. This was a non-randomized retrospective study. It appears that the threshold for increased risk may have decreased from <40% ppoFEV1 in the open group to <30% in the VATS group. (Based on data from Berry et al. [93])

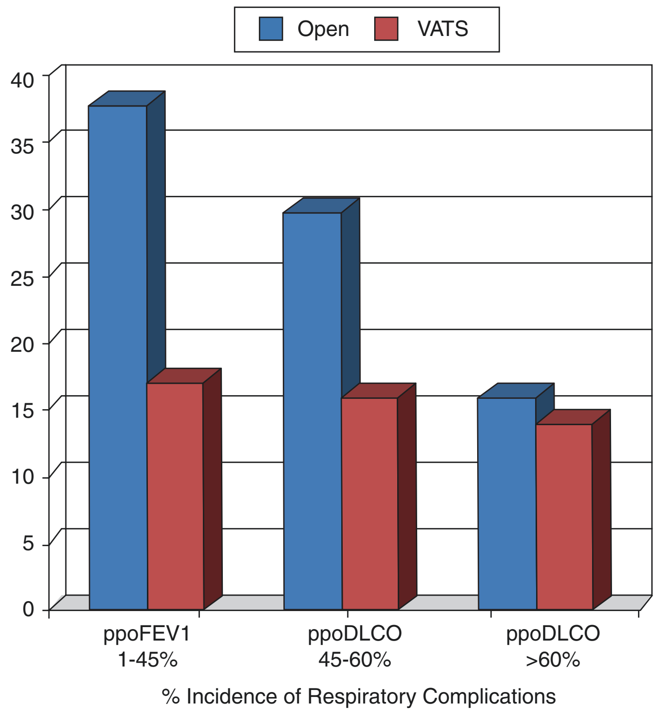

Fig. 2.17 A comparison of the incidence of postoperative respiratory complications after open (thoracotomy) vs. VATS lobectomies for lung cancer. ppo = predicted postoperative value. DLCO = diffusing capacity for carbon monoxide. This was a non-randomized retrospective study. It appears there is a threshold for increased risk in open procedures under 60% ppoDLCO. A threshold for VATS procedures could not be identified; however, there were very few patients with a ppoDLCO <40% in this study. (Based on data from Berry [93])

mortality and specific major complications (see Fig. 2.18). Although this tool is very useful to explain to patients and families the perioperative risks from a specific operation, it does not allow for a stratified approach to preoperative evaluation for an individual patient. A combined cardiorespiratory algorithm specific to patients having lung cancer surgery is presented in Fig. 2.19 [95].

Perioperative Considerations in Thoracic Malignancies

The majority of patients presenting for major pulmonary surgery will have some type of malignancy. Because the different types of thoracic malignancies have varying implications for both surgery and anesthesia, it is important for the anesthesiologist to have some knowledge of the presentation and biology of these cancers. By far the most common tumor is lung cancer. It is estimated that at present rates over 210,000 new cases of lung cancer occur in the United States annually. Of these only 26% will be resectable. However, this represents >55,000 patients/year who can be offered potentially curative surgery [96]. Lung cancer is currently the leading cause of cancer deaths in both sexes in North America subsequent to the peak incidence of smoking in the period 1940–1970 (Fig. 2.20) [97]. The mortality rate from lung cancer has shown a slight decrease in the last decade for men related to decreased smoking rates and appears to have plateaued in women.

Lung cancer is broadly divided into small-cell lung cancer (SCLC) and non-small cell lung cancer (NSCLC), with about 75–80% of these tumors being NSCLC. Other less common and less aggressive tumors of the lung include the carcinoid tumors (typical and atypical) and adenoid cystic carcinoma. In comparison with lung cancer, primary pleural tumors are rare. They include the solitary fibrous tumors of the pleura (previously referred to as benign mesotheliomas) and malignant pleural mesothelioma (MPM). Asbestos exposure is implicated as a causative effect in up to 80% of MPM. A dose-response relationship is not always apparent, and even brief exposures can lead to the disease. An exposure history is often difficult to obtain because the latent period before clinical manifestation of the tumor may be as long as 40–50 years.

Tobacco smoke (both primary and secondhand) is responsible for approximately 90% of all lung cancers, and

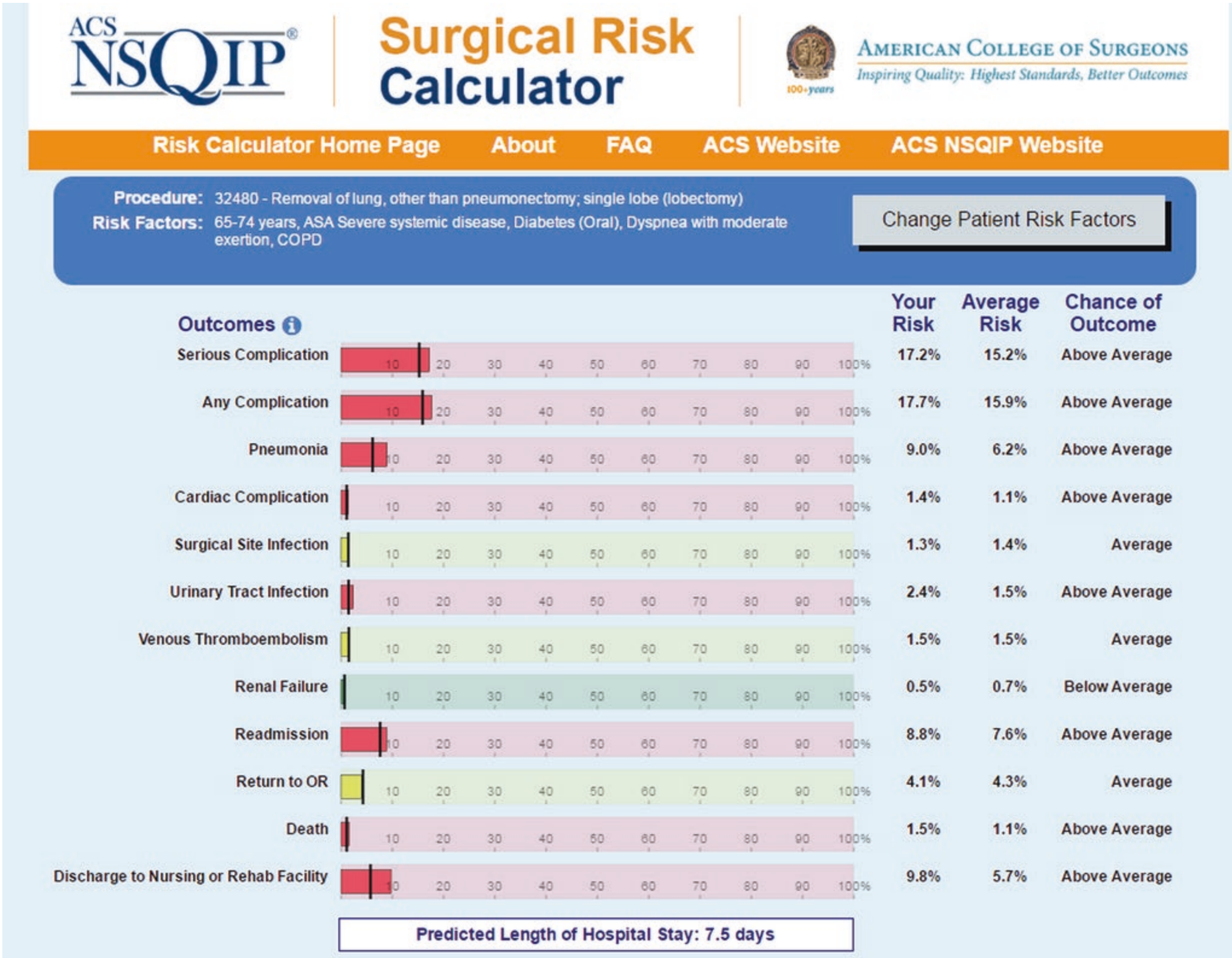

Fig. 2.18 A calculation of perioperative risks for a theoretical 70-year-old, nonobese, male with COPD and non-insulin-dependent diabetes scheduled for a pulmonary lobectomy using the NSQIP web-based calculator (http://riskcalculator.facs.org/RiskCalculator) (Note there is no quantification of the severity of COPD using this calculator)

the epidemiology of lung cancer follows the epidemiology of cigarette smoking with approximately a three-decade lag time [98]. Other environmental causes include asbestos and radon gas (a decay product of naturally occurring uranium) which act as cocarcinogens with tobacco smoke. For a pack-a-day cigarette smoker, the lifetime risk of lung cancer is approximately 1 in 14. Smoking cessation reduces the risk of lung cancer but never to that for never smokers. Assuming current mortality patterns continue, cancer will pass heart disease as the leading cause of death in North America in this decade.

Prior to pulmonary resection, lung cancer patients will undergo staging tests to determine the extent of their cancer. These will include radiographic tests such as CT scan, positron emission tomography (PET), and in some cases brain magnetic resonance imaging. Additionally, many patients will have invasive mediastinal staging to determine histologically whether or not the cancer has spread to the mediastinal lymph nodes. In general, if mediastinal lymph nodes contain cancer, primary surgical resection is not recommended. Cervical mediastinoscopy which is performed under general anesthesia has been the gold standard for invasive mediastinal staging. More recently, endobronchial ultrasound with transbronchial needle aspiration (EBUS-TBNA) and endoscopic ultrasound mediastinal node biopsy have become popular. These procedures may be done under topical anesthesia with intravenous sedation and are less invasive than mediastinoscopy. Regardless of the technique, the indication for invasive mediastinal staging is the same. Any patient with enlarged mediastinal nodes on CT or FDG-avid ("hot") nodes on PET scan should have invasive staging. Additional indications include T3 or T4 tumors, central tumors, and those with suspicion of hilar lymph node involvement [99].