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The Development of Thoracic Anesthesia and Surgery

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Introduction

The history of anesthesia for thoracic surgery incorporates much of the history of anesthesia because contemporary thoracic anesthesia is a culmination of advances in all aspects of anesthesia. Knowledge and expertise with preoperative evaluation, airway management, intraoperative monitoring, pharmacologic agents, regional anesthesia, and intensive care management are all crucial for the thoracic anesthesiologist. Anesthesia for thoracic surgery encompasses over 100 years of advances in anesthesia techniques, and these techniques are still evolving and improving. Complex thoracic procedures are now routinely performed on frail patients with associated comorbidities, who may not have been considered candidates in the past, thanks to improvements in anesthesia and surgical techniques.

Before advances in general anesthesia techniques, specifically positive pressure ventilation and controlled respiration with endotracheal intubation, surgery that trespassed the chest wall was performed very rarely because it was both dangerous to patients and very difficult for surgeons. Because of the unique challenges of performing surgery on an open thorax safely, the delivery of thoracic anesthesia is a relatively late development in the history of anesthesia. During the early 20th century, thoracic surgery procedures were frequently attempted through local anesthesia. The pneumothorax created after opening of the chest wall was viewed as invariably fatal. That was changed based on the observation that, during World War I, soldiers with large chest openings could survive.

Inhalational anesthesia was introduced in the 1840s, but it took another 100 years before much headway was made in anesthesia for thoracic surgery. Thoracic surgery could only flourish as a specialty once progress was made in thoracic anesthesia; the development of no other surgical subspecialty relied so heavily on the refinement of anesthesia techniques. Although intrathoracic procedures have become routine, thoracic surgeons and anesthesiologists retain a unique relationship; coordination between surgeon and anesthesiologist is especially critical in thoracic surgery.

Today, knowledge of thoracic anesthesia is more important than ever; as the scope of thoracic surgery has broadened, so has the range of anesthesia practice for it. One-lung ventilation (OLV), critical to thoracic anesthesia, is essential for more and more thoracic approaches to lung, esophageal, mediastinal, spinal, and cardiac procedures. Minimally invasive approaches to intrathoracic procedures rely heavily on OLV for adequate, still surgical exposure. Because of the wide variety of double lumen endotracheal tubes and endobronchial blockers that are currently available, OLV can be provided safely and reliably for virtually all patients. With mastering lung separation, in addition to being knowledgeable about the tools needed, it behooves the thoracic anesthesiologist to have a sound understanding of the physiology of OLV for preventing hypoxemia owing to the transpulmonary shunt.

Early History of Thoracic Anesthesia

John W. Strieder, a seasoned thoracic surgeon of the early 20th century, described “the good old days” of thoracic anesthesia colorfully: “the period of operation was, with dismaying frequency, a race between the surgeon and the impending asphyxia of the patient.”[1] Aurelius Cornelius Celsus (25 BC–AD 50), the Roman encyclopedist, knew 2000 years ago that entering the thorax posed unique dangers to the patient. In *De Medicina*, Celsus describes “for the belly indeed, which is of less importance, can be laid open with the man still breathing; but as soon as the knife really penetrates to the chest…the man loses his life at once.”[2] This is an early description of the “pneumothorax problem”: opening the chest immediately causes an open pneumothorax. When the lung is exposed directly to the atmosphere, it will rapidly collapse because of the loss of the normally negative intrapleural pressure. In addition, air would be transferred between the two lungs known as “pendulluft,” and the collapsed lung would paradoxically expand during expiration and collapse during inspiration. To further terrify the surgeon, vigorous side-to-side movement of the mediastinum could occur, known as "mediastinal flapping," that could compress the nonoperative lung. In the lateral decubitus position, it would result in "mediastinal shift" and hypotension. Not surprisingly, respiratory and hemodynamic compromise would ensue as the patient would struggle to breathe spontaneously. Hence most thoracic procedures were limited to the extrathoracic chest wall until the 1930s. Only very brief intrathoracic procedures were possible without patient asphyxiation.

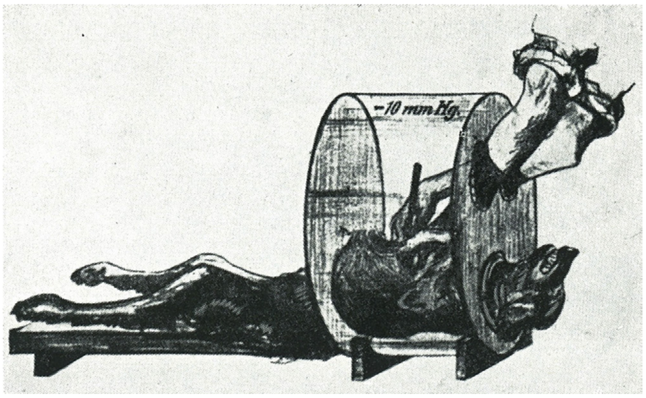
Most areas of surgery flourished after the discovery of inhalational anesthesia in the 1840s, and the delivery of general anesthesia became routine. Until the 1930s, delivery of inhalational anesthesia was typically by mask or open drop administration, using ether or chloroform with or without nitrous oxide. Because patients would typically breathe spontaneously, they could control their own depth of anesthesia with their own respirations. Muscle relaxants were not developed yet, and endotracheal intubation was considered an invasive procedure and only rarely used by a few experts. Most thoracic procedures performed were the same pathology that concerned Celsus 2000 years ago: management of empyema, pulmonary abscess, and tuberculosis. Without antibiotics, patients would frequently present for surgery with copious secretions and formidable coughs. It was common to keep a patient only lightly anesthetized to keep the cough reflex intact to protect the lungs from gastric aspiration and to allow the patient to clear their own copious secretions. Envisioning a harrowing scene of a lightly anesthetized patient choking on their secretions with an unprotected airway, it is hardly surprising that thoracic surgery remained in its infancy well into the 20th century. Better operating conditions and improved anesthesia techniques were needed to allow thoracic surgery to flourish.

Before the discovery of antibiotics, most thoracic procedures were performed to treat infection, opening the pleural cavity did not always result in an open pneumothorax because prolonged infections often resulted in adhesions between the lung and chest wall with a loculated empyema. The utility of these adhesions was known, and repeated aspirations were sometimes attempted to promote adhesion formation before surgery. Alternatively, air or water could be injected into the pleural space as an irritant to promote adhesion formation preoperatively.[3,4] "Muller's handgrip" was another primitive method used to cope with the pneumothorax problem: while the chest was open, the surgeon would pull the lung into the wound to plug the thoracotomy incision.[5] Pulmonary resections were frequently performed in a staged manner and had a very high mortality. A snare or tourniquet technique would be used to facilitate a quick resection, and then a reoperation would be needed to remove necrotic tissue later. It is not surprising that sepsis was not uncommon from the remaining necrotic tissue. A review from 1922 reported a mortality rate of 42% for lobectomy, and as high as 70% for cases that involved more than one lobe.[6] Clearly, surgeons and patients needed safer, less harmful solutions.

Differential Pressure Breathing

The German surgeon Ernst Ferdinand Sauerbruch developed the first promising solution to the "pneumothorax problem." In 1893, his mentor, Johann von Mikulicz-Radecki, urged him to address the difficulty of operating with an open pneumothorax. His solution, differential pressure breathing, became the principal method for management of ventilation in thoracic surgery until World War II. In Sauerbruch's experiments on dogs, he found that, during thoracotomy, spontaneous ventilation was maintained and the lung did not collapse if it was exposed to a pressure 10 cm H_2O below atmospheric pressure.[7] After his experimental thoracotomies on dogs, he applied the technique to humans (Fig. 1.1). To maintain the negative pressure, a large negative pressure chamber was needed that would maintain the normal negative intrapleural pressure. The patient and surgical team were placed within the steel negative pressure chamber while the patient's head protruded from the chamber and was exposed to atmospheric pressure. With the negative pressure applied directly to the lung, the patient could breathe spontaneously and the lung would remain inflated.

Sauerbruch championed his pneumatic chamber technique as a physiologic method, and differential pressure breathing was widely adapted. However, Sauerbruch's method was very impractical because of the large, expensive, negative pressure chamber that was needed. Operating conditions were less than ideal. Rudolph Nissen described the limitations of this operating suite: "the surgeon and his assistants had very little room to move; the heat was almost unbearable; and, finally, it was extremely difficult to communicate satisfactorily with the anesthetist outside the chamber."[8] An anesthetist would be outside the chamber at the patient's airway and could only communicate with the



• **Fig. 1.1** Sauerbruch's experimental negative pressure box for performing thoracotomies on dogs. The dog's chest is enclosed in the box, in which the pressure is −10 mm Hg (1904). (From Mushin WW, Rendell-Baker L, eds. *The Principles of Thoracic Anesthesia*. Springfield, IL: Charles C Thomas; 1953. Copyright Wiley-Blackwell.)

surgeon within the chamber by phone over the loud whirring of pumps.

A more practical alternative method for using differential pressure to maintain lung inflation was developed in parallel by a colleague of Sauerbruch's, Ludolph Brauer. His alternative method for using differential pressure breathing was published alongside Sauerbruch's. Brauer's method used a positive pressure chamber to increase the intrapulmonary pressure. Brauer's chamber was simply a large box and the patient's head was placed within it after the induction of anesthesia, and anesthesia was maintained with the patient breathing oxygen and chloroform spontaneously. Before the chest was opened, compressed air would be added to the chamber to raise the pressure above atmospheric pressure, and this would prevent the development of an open pneumothorax. The anesthetist would have no access to the head during the procedure.[7] Brauer's design resembles specialized helmets developed for delivering continuous positive airway pressure (CPAP) or for noninvasive ventilation that could be used for treating respiratory failure.[9]

Although Brauer's positive pressure technique was simpler than Sauerbruch's, Sauerbruch had his devotees in Europe and the United States. In 1909, the American surgeon Willy Meyer created his own "universal differential pressure chamber," a modified version of Sauerbruch's negative pressure chamber.[10] Meyer's chamber was even more complicated than Sauerbruch's; it included both a positive and negative pressure chamber. The overall chamber was 1000 cubic feet in volume and could contain up to 17 people. The patient, anesthetist, and an assistant could be enclosed in the positive pressure chamber within the negative pressure room. By using both chambers, the normal negative intrapleural pressure gradient could be maintained, either by applying positive pressure to the head, negative pressure to the open chest, or both. Meyer described "if the differential pressure in the universal pressure is composed of part vacuum and part pressure, only the patient is exposed to the full differential, while all others are exposed only to the component… the anesthetizer to the positive fraction and the surgeon… to the negative fraction, which still more reduces any possibility of detrimental effects on the users of the chamber." This was the only negative pressure chamber built for this purpose in America, and Meyer also used it for improving wound drainage and lung expansion postoperatively.[11]

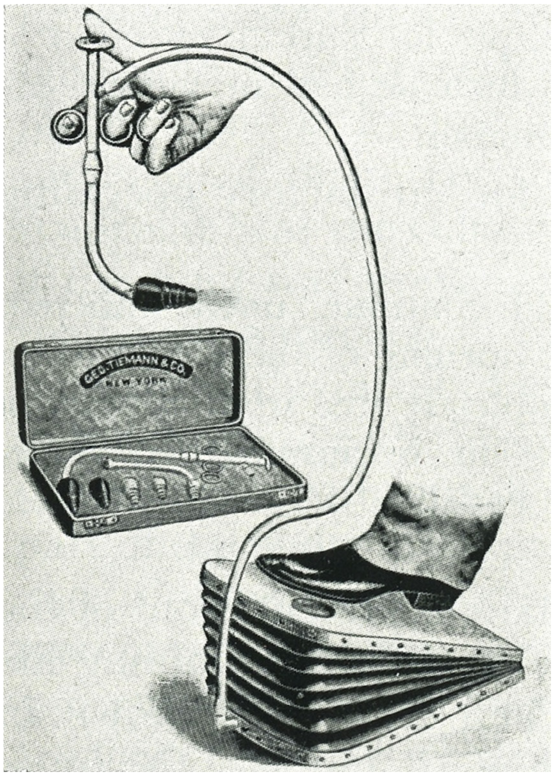
Both the positive pressure and negative pressure methods relied on maintaining a pressure gradient between the air outside and within the lungs, otherwise known as differential pressure breathing. Differential pressure breathing was successful at preventing the formerly inevitable open pneumothorax after thoracotomy; however, it was doomed to become a historical relic because it provided dangerously inadequate ventilation. Hypoventilation, hypercarbia, hypoxemia, and impaired venous return were significant problems during prolonged cases and clinical deterioration was not uncommon. Meyer attributed the cause of unexplained shock to hypercarbia, and he recommended applying rhythmic variations in pressure coordinated with spontaneous respirations to assist with ventilation. Remarkably, although this method of preserving respiration with an open chest seems so cumbersome to modern readers, Sauerbruch and his followers felt it was endotracheal intubation that was impractical and unsafe. Meyer felt "combining intubation and masks appears so manifestly inadequate and dangerous for everyday surgery that it cannot deserve preference over apparatus leaving the mouth of the patient unincumbered [sic]."[10]

Tracheal Insufflation and Endotracheal Anesthesia

Tracheal insufflation anesthesia, an alternative method for preventing the development of the open pneumothorax, became popular in America in the early 20th century. This new method is the clear precursor to the endotracheal anesthesia we use today. Because of widespread skepticism about the routine use of tracheal intubation, the development did not follow a smooth path. Tracheal intubation and mechanical ventilation were not new discoveries; many pioneers deserve credit in the development of intubation, laryngoscopy, and positive pressure ventilation, especially considering how much skepticism they faced.

Andreas Vesalius used tracheal intubation for positive pressure ventilation of a pig in 1543. He performed a tracheotomy and passed a reed into the trachea of a pig and blew into the tube to provide artificial ventilation during a thoracotomy and thus prevented a potentially fatal open pneumothorax. His findings went unnoticed and were only later rediscovered. In 1788, Charles Kite resuscitated victims of drowning from the River Thames using curved metal cannulas that he placed blindly in the trachea. Soon after the development of inhalational anesthesia, there were early enthusiasts trying to apply these resuscitation techniques to anesthesia delivery. In 1869, Friedrich Trendelenburg used a tracheostomy tube with an inflatable cuff to administer chloroform during head and neck surgery. William MacEwan, a Scottish surgeon, is credited with the first use of oral endotracheal intubation for an anesthetic. On July 5, 1878, MacEwan placed a flexible metal tube in the larynx of an awake patient who was to have an oral tumor removed at the Glasgow Royal Infirmary.[12] In 1885, Joseph O'Dwyer, a pediatrician unaware of earlier uses of intubation, performed blind oral tracheal intubations on children suffering from diphtheria.[13] O'Dwyer designed a rigid tube with a conical tip that could occlude the larynx to facilitate positive-pressure ventilation. In 1893, George Fell attached O'Dwyer's metal tube to a bellows and T-piece, creating the Fell-O'Dwyer apparatus. Fell used the apparatus to provide ventilatory support for opiate-induced respiratory depression (Fig. 1.2).

By the 1890s, there was interest in applying endotracheal anesthesia technique to thoracic surgery in an attempt to prevent the pneumothorax problem. In 1896, the French surgeons Tuffier and Hallion reported on their use of tracheal



• **Fig. 1.2** The Fell-O'Dwyer Apparatus (c. 1888). O'Dwyer's laryngeal tube has a curved right angle and uses fitted, interchangeable, conical heads of different sizes designed to fit securely into the larynx. Rings were provided for the operator's fingers and the operator's thumb was placed over the expiratory orifice during inflation. (From Mushin WW, Rendell-Baker L, eds. *The Principles of Thoracic Anesthesia*. Springfield, IL: Charles C Thomas; 1953. Copyright Wiley-Blackwell.)

intubation with artificial ventilation to perform thoracotomies on animals.[12] They used a device with a bellows for the rhythmic inflation of the lungs, and a water valve that could control the degree of resistance to expiration, a precursor to the modern use of positive end-expiratory pressure (PEEP). Inspired by Tuffier and Hallion, Rudolph Matas made modifications to the Fell-O'Dwyer apparatus to make it appropriate for use during surgery. Matas was convinced that such a device would be ideal for thoracic cases. His modifications included adding a graduated cylinder for delivery of precise volumes of gases and a mercurial manometer for the measurement of intrapulmonary pressures. He also modified it to be a simple anesthesia machine by adding an intralaryngeal cannula connected by a stopcock to a rubber tube and funnel that could be used for administering chloroform.[14]

These early pioneers of endotracheal techniques were using endotracheal tubes that were similar in size to the trachea, through which inspiration and exhalation occurred. In 1907, Barthélemy and Dufour used a new method called "tracheal insufflation."[12] A thin tube was placed in the trachea and gases were continuously insufflated under positive pressure into the lower portion of the trachea. Expired gases exited between the tracheal tube and the tracheal wall. Meltzer and Auer, American physiologists, used this technique extensively in animal studies and showed that curarized dogs could be anesthetized and kept alive by blowing air and ether continuously into a tube inserted into the trachea. Gas exchange would still occur "without any normal or artificial rhythmical respiratory movements whatever" because expired gases could escape around the tracheal tube.[15] This was essentially an improvement of Brauer's method of continuously applying positive pressure; however, because dead space was decreased significantly by the placement of the cannula in the trachea, gas exchange was improved although still not optimized.

Charles Elsberg, a thoracic surgeon in New York City, was familiar with Meltzer and Auer's research and applied this method to thoracic surgery. He first used tracheal insufflation to resuscitate a myasthenic patient who had become cyanotic and pulseless. The technique was successful in that she regained spontaneous circulation; however, she did not regain consciousness so the resuscitation was eventually discontinued. Elsberg modified Meltzer and Auer's apparatus by replacing the bellows with an electric motor. He also placed the tracheal cannula under visualization after topicalization of the larynx with cocaine by using either a Killian bronchoscope or a Chevalier Jackson laryngoscope.[16] In February 1910, Elsberg presided over the historical first use of tracheal insufflation anesthesia for thoracotomy.[17] The thoracic surgeon Howard Lilienthal recruited Elsberg to help him treat a butcher with a 13-month history of productive cough. The presumptive diagnosis was lung abscess, and Lilienthal wanted to attempt an operative cure. When the pleura was opened, 15 mm Hg was applied intratracheally, and the lung was noted to be "two-thirds of its capacity, mottled, and rosy pink in color." Different pressures were applied and the lung collapsed and swelled. Elsberg periodically interrupted the insufflation every 2 to 3 minutes, to allow the lungs to collapse and facilitate carbon dioxide elimination, thus resembling modern positive-pressure ventilation. After his success in this landmark surgery, Elsberg promoted tracheal insufflation for all surgeries requiring general anesthesia. Only 1 year later, he published on his experiences using this technique to anesthetize over 200 patients.[18] Elsberg's method of tracheal insufflation is very similar to the modern practice of oxygen insufflation during rigid bronchoscopy that was first introduced by Sanders in 1968.[19]

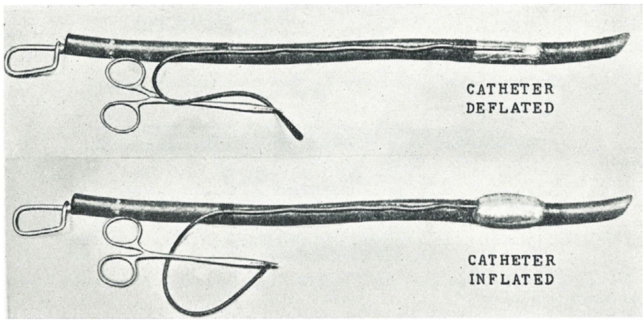
Endotracheal Intubation and Laryngoscopy

After Elsberg's triumph, tracheal insufflation anesthesia became the most popular anesthetic method for thoracic surgery in the United Sates in the 1920s and 1930s. Differential pressure anesthesia was still preferred in Europe for thoracic procedures. Tracheal insufflations remain popular in Europe only for head and neck procedures where mask or hand drop techniques could interfere with the surgical field. A major reason for the reluctance to widely adopt the tracheal insufflation technique in Europe was the dominance of Sauerbruch and his unwillingness to adopt any other method. Sauerbruch's own assistant, Giertz, performed experiments on animals that showed that rhythmic inflation of the lungs was superior to differential pressure breathing. He also showed that differential pressure anesthesia resulted in inadequate ventilation, hypercarbia, impaired venous return, and circulatory collapse.[7] Although better than the alternative, tracheal insufflation was far from perfect. Carbon dioxide accumulation would occur if gas flow was interrupted. This was addressed with modifications to Elsberg's apparatus that periodically stopped airflow to allow the lungs to collapse. Also, barotrauma was possible when dangerously high intrapulmonary pressure occurred when the return of gas was impeded. Alveolar rupture and surgical emphysema could occur and were called "wind-tumor," likely caused by an interruption in the exit of expired gases when laryngospasm occurred around thin tracheal insufflation catheters.[12]

Another impediment to the routine use of endotracheal techniques was that blind placement of endotracheal tubes was the norm. Instruments for direct laryngoscopy existed by the 1920s, but were infrequently used. Blind placement required considerable skill and could be traumatic and cause airway laceration from the rigid tube. Alfred Kirstein, a physician in Berlin, is credited with inventing the first direct laryngoscope in 1895; before 1895, direct visualization of the larynx was considered impossible. Kirstein's "autoscope" was not used for anesthesia, but it was the prototype for many laryngoscopes to follow.[20] In 1913, Chevalier Jackson developed his own laryngoscope and described proper positioning and technique for laryngoscopy in a landmark paper.[21] In 1941, Robert Miller created the still familiar Miller blade, its origins clearly rooted in the laryngoscopes of Kirstein and Jackson. Sir Robert Macintosh released his curved blade in 1943, that remains until today the most popular laryngoscope blade in the world because of its ease of use.

Improvements in endotracheal tubes occurred alongside these developments in direct laryngoscopy. World War I produced many wounded warriors requiring reconstructive surgery for head and neck injuries. In 1919, the British anesthetists Ivan Magill and Stanley Rowbotham were assigned to work with the British army plastics unit. Under pressure to provide unhindered access to the face and airway, they became experts in blind nasal intubations. They rejected the popular insufflation technique and used larger tubes that permitted inhalation and exhalation to occur through the tube. Magill's wide-bore red rubber tubes resisted kinking and adjusted to the contours of the upper airway. They remained the standard endotracheal tube until plastic tubes were introduced.

The next step was the development of the cuffed tracheal tube. Without this, controlled positive-pressure would not be effective. In the 19th century, there were sporadic attempts at using cuffed tubes. In 1871, Trendelenburg used a cuffed tracheotomy tube, as did Eisenmenger in 1893, and Dorrance in 1910.[22] None of these attempts sparked much interest in cuffed endotracheal tubes. In 1928, Guedel and Ralph Waters introduced their endotracheal tube with a detachable inflatable cuff, and became strong advocates for the routine use of cuffed endotracheal tubes (Fig. 1.3).[23] Guedel performed his famous "dunked dog" demonstrations to show the effectiveness of the tube's seal. He submerged his intubated and sedated dog in an aquarium, from which he emerged unscathed.[24] Not only would this tube facilitate the use of controlled positive-pressure ventilation, it could prevent aspiration of gastric contents, no longer making it necessary for patients to be kept lightly anesthetized to preserve the cough reflex. With deeper planes of anesthesia, the trachea could be suctioned and operating conditions improved. Through hyperventilation, it was often possible to suppress respiratory efforts even without muscle relaxation. Control of ventilation and protection from aspiration of gastric contents represent an historic milestone in patient ventilation strategy.



• **Fig. 1.3** Guedel and Waters "new intratracheal catheter" (1928). The catheter is shown deflated, and then inflated. The tube was 14 inches along, and made of rubber. (From Mushin WW, Rendell-Baker L, eds. *The Principles of Thoracic Anesthesia*. Springfield, IL: Charles C Thomas; 1953. Copyright Wiley-Blackwell.)

Even though all of the components of airway management necessary to conquer the "pneumothorax problem" existed by 1930, unfortunately, these methods did not immediately gain widespread use. Sauerbruch's differential pressure breathing was still commonly used in Europe until World War II. Cuffed endotracheal tubes were not initially deemed necessary and took many years to gain widespread approval. In 1948, a review of 309 anesthetics for thoracic cases still advocated routine use of steep Trendelenburg to promote drainage of secretions around uncuffed endotracheal tubes and still did not recommend routine use of controlled positive-pressure ventilation.[25]

Milestones in Thoracic Surgery

Thoracic surgery progressed at a snail's pace in the 1920s. Improvements in anesthetic techniques in the 1930s made several advances in thoracic surgery possible. In 1929, Harold Brunn used the individual-structure ligation technique to replace the two-stage snare or tourniquet technique for lung resection. This new technique reduced complications, such as air leak, tension pneumothorax, hemorrhage, and infection from necrotic residual tissue.[26] Rudolph Nissen performed the first two-stage pneumonectomy in 1931, soon followed by Evarts Graham's one-stage total pneumonectomy for lung cancer in 1933.[27,28] The trajectory of thoracic surgery was changing; opening the chest had been so risky that it had been reserved only for refractory infections, but now the role of thoracic surgery for treating malignancy could flourish and overshadow its use for the treatment of infection. The addition of routine postoperative pleural drainage in the 1930s by closed chest thoracostomy also aided surgical progress. Advances in esophageal surgery also occurred in the 1930s. The first transthoracic esophagectomy with an intrathoracic esophagogastric anastomosis was performed successfully in Japan in 1933.[29] Thoracic surgery was starting to flourish as thoracic anesthesia improved.

Thoracic Surgery Under Regional Anesthesia

Regional anesthesia for thoracic surgery had its advocates before the 1940s. Proponents of regional anesthesia claimed its safety because it kept the cough reflex intact and maintained spontaneous ventilation. These are still valuable attributes of regional anesthesia. In a 1936 review of thoracic anesthesia, Magill describes spinal anesthesia as an excellent technique for a wide range of thoracic procedures, even pneumonectomy! He recognized that regional anesthesia is best for cooperative patients, as it still is today. The awake patient could assist more easily with breath-holding because controlled ventilation was not routine during general anesthesia.[30] Not everyone was so enamored with spinal anesthesia for thoracic surgery. Nosworthy declared, "I like my anesthetic technique to be such that I have the whole situation under control. I do not feel that I am in a position to cope with any emergency when chest surgery is performed under spinal anesthesia."[31] Nosworthy went on to describe an inadequate cough reflex and frequent dyspnea during open chest procedures under spinal anesthesia. It is interesting that tubeless thoracic procedures are presently gaining widespread popularity because of concerns that positive pressure ventilation has the potential to injure the lung parenchyma.

Emergence of One-Lung Ventilation

The union of direct laryngoscopy, tracheal intubation, cuffed endotracheal tubes, and controlled ventilation set the stage for the development of OLV in the 1930s. Lung separation for prevention of contamination or for surgical exposure was the next frontier. Lung surgery was still frequently performed for infection, and spillage from the infected lung was a frequent problem in the setting of copious secretions. Gale and Waters published the first use of OLV for thoracic surgery in 1931.[32] They used a long standard rubber Guedel-Waters tube that was softened with hot water to have a lateral bend. It was placed in the trachea, and then blindly advanced into either bronchus until resistance was met. In addition to preventing the "pneumothorax problem" by isolating the lung exposed to ambient pressure, this lung isolation technique also provided the advantage of an immobile lung and a quiet surgical field. Their technique was elegant in its simplicity, but not widely practiced because blind placement was difficult and tube positioning could be unstable.

Rovenstine tried to improve upon Gale and Waters' endobronchial technique. In 1936, he described the use of a single lumen endobronchial tube with two cuffs that could ventilate either one lung or both.[33] The endobronchial tube was made of woven silk and would be molded in hot water to have a lateral curve, and then advanced blindly into either bronchus as Gale and Waters described. If only the upper cuff was inflated above the carina, both lungs could be ventilated. The endobronchial cuff would occlude the other mainstem bronchus when inflated, thus enabling OLV. This tube also did not gain wide popularity because of the difficulty and instability of placement.

Bronchial Blockade

The initial use of bronchial blockers also began in the 1930s. By placing a foreign body to obstruct ventilation in the intended bronchus to a lung or lobe, ventilation is interrupted, and the unventilated lung distal to the obstruction will collapse. Archibald described the first use of a bronchial blocker in 1935; he used an inflatable balloon attached to the end of a rubber catheter to occlude the main bronchus of the affected lung during lobectomy and prevent contamination by spillage of pus to the healthy lung. He used x-ray films to confirm appropriate placement.[34] Because of its complexity, this particular technique with x-ray guidance did not gain popularity, however, the use of a balloon for bronchial blockade had significant potential and would undergo several refinements and is still used today.

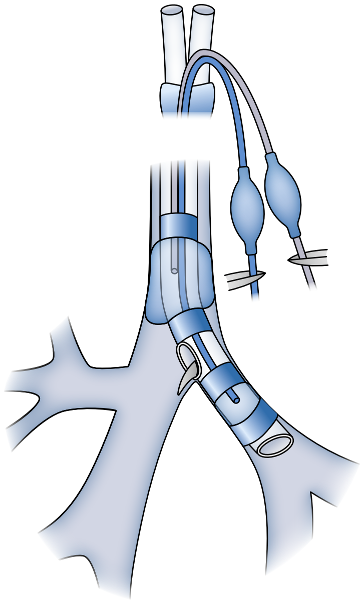
Magill improved Archibald's design. In 1936, he used a similar bronchial blocker but placed it under direct vision using a tracheoscope, thus eliminating the need for x-ray guidance. His bronchial blocker was a long tube with a balloon at the distal end and was inserted alongside an endotracheal tube. Magill recommended the use of the blocker for the control of secretions, and it had a suction catheter for the blocked lung. Magill realized the blocker could improve surgical exposure by causing atelectasis of the operative lung. He recommended placement after topicalizing the larynx but before induction of general anesthesia, so that secretions could be suctioned during induction. In addition, Magill designed an endobronchial tube for lung separation; his endobronchial tube was also placed under direct vision using an endoscope through its lumen.[30] Many other instruments were used to provide bronchial blockade before the development of the plastic bronchial blockers that are currently used. In 1938, Crafoord used a ribbon gauze tampon for the control of secretions for "bronchial tamponage." The tampon was inserted using a rigid bronchoscope into the selected bronchus, while the healthy lung was ventilated by an endotracheal tube at the carina.[35] None of these techniques were commonly used because they required considerable skill and expertise. Thompson's bronchial blocker was introduced in 1943 and is the prototype for all the blockers to follow. It had a stylet and was placed through a rigid bronchoscope, and it consisted of two tubes fused together. One tube inflated a gauze-covered balloon, and the other was for applying suction to the blocked bronchus.[36]

In the 1950s, several single-lumen endotracheal tubes were developed with incorporated bronchial blockers: Steurtzbecher in 1953, Vellacott in 1954, Macintosh and Leatherdale in 1955, and Green in 1958.[37–39] These are the predecessors of the Uninvent tube, which was the first modern endotracheal tube with incorporated bronchial blockade. The Univent tube is a large endotracheal tube with a small internal lumen that contains a retractable cuffed bronchial blocker.[40] At the end of the procedure, once OLV is no longer needed, the blocker can be retracted to its internal lumen, and the tube functions as a conventional single lumen tube. Although this design is convenient, the Univent tube has a larger external diameter than a single-lumen tube of the same internal diameter, making it more traumatic to place and potentially causing increased air-flow resistance.[41]

Fogarty embolectomy catheters, Swann-Ganz catheters, and Foley catheters have all been attempted to be used as bronchial blockers. Fogarty catheters, mainly designed for vascular surgery, are described as providing successful bronchial blockade in numerous case reports.[42] However, because they were not designed for this use, they have limitations for this purpose. Their low-volume, high-pressure spheric shaped cuffs could damage bronchial mucosa, and there is no communicating channel for suction or oxygen insufflation. Positioning may be difficult, especially in the left main bronchus, because there is no steering mechanism for guiding it. All the modern balloon-tipped bronchial blockers used in clinical practice address these design flaws.[43–45] All use balloons with low-pressure, high-volume cuffs to decrease bronchial trauma, and all are intended to be placed with guidance by a 4.0-mm flexible fiberoptic bronchoscopy.

Double-Lumen Endobronchial Tubes

The first known description of a double-lumen tube (DLT) dates back to 1889 when Head used a tube with two lumens to study respiratory physiology in dogs. In 1949, Bjork and Carlens designed the first DLT for thoracic surgery, although it was originally intended for use in differential bronchospirometry to evaluate the predicted residual lung capacity post-pneumonectomy.[46] Carlens tube was designed for intubation of the left main bronchus; because endobronchial placement was performed blindly, a carinal hook was included in the design to grip the carina and to aid placement (Fig. 1.4). Bryce-Smith modified the Carlens tube in 1959 by eliminating the carinal hook because it did not in practice aid with the placement.[47] Both of these tubes could be used for right or left-sided procedures with few exceptions because ventilation could occur through either the tracheal or bronchial lumen, depending on what was needed for surgical exposure.



• **Fig. 1.4** Bjork and Carlens Double Lumen Catheter (1949). This is the first double-lumen endobronchial tube intended for intubation of the left mainstem bronchus. Note the presence of the carinal hook. (From Mushin WW, Rendell-Baker L, eds. *The Principles of Thoracic Anesthesia*. Springfield, IL: Charles C Thomas; 1953. Copyright Wiley-Blackwell.)

Because left-sided DLTs could not be used for left pneumonectomy, where the left main bronchus is cut close to the carina, a right-sided DLT was sought. Early DLTs were all left-sided because intubating the right main bronchus with an endobronchial lumen without occluding the opening of the right upper lobe bronchus was challenging. In 1960, Bryce-Smith and Salt described a right-sided DLT that included a slit in the endobronchial cuff for ventilation of the right upper lobe, and White designed a right-sided version of the Carlens tube with a ventilating orifice in the endobronchial cuff.[48,49]

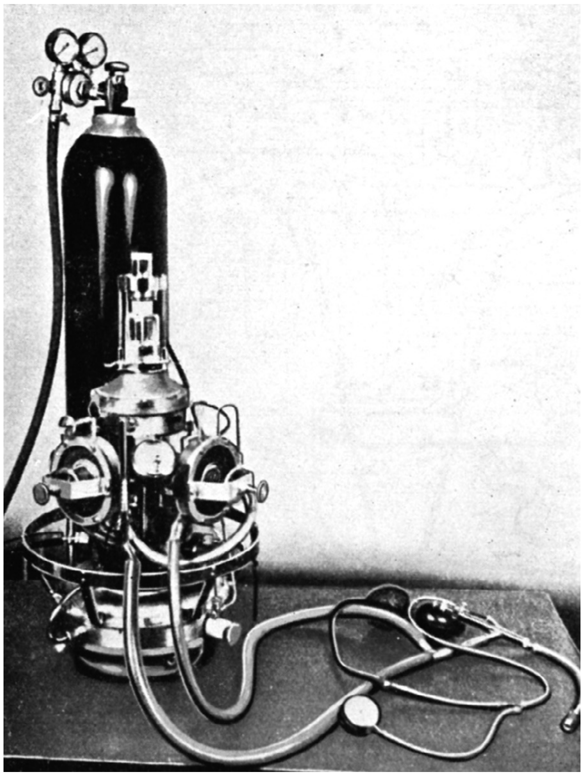
Early DLTs were bulky, difficult to use, and potentially dangerous. Occlusion by kinking, trauma from carinal hooks, high airway resistance during OLV, and difficult blind placement were common. In 1962, Robertshaw introduced a new DLT that closely resembles those in use today.[50] He removed the carinal hook, and he introduced the novel cross-section D-shaped lumens that provided a larger cross-sectional area and reduced resistance to airflow compared with the older round lumens. Disposable plastic DLTs have replaced the older red rubber tubes, but red rubber reusable tubes are still used in many parts of the world where resources are scarce. Of interest, a European company (P3 Medical, Bristol UK) is currently manufacturing a single-use red rubber Robertshaw design DLT.

It was not until the 1980s that flexible fiberoptic bronchoscopy became available for precise positioning DLTs in the operating room (OR). Remarkably, DLTs were in use for 30 years before this development of flexible bronchoscopy, and placement was essentially blind and relied on clinical examination. The use of small flexible bronchoscopes (4.0 mm) for precise evaluation of the positioning of DLTs or endobronchial blockers is now a common practice. Newer video bronchoscopes have replaced fiberoptic bundles with video cameras that project higher quality video images on an external monitor. In fact, almost all endobronchial blockers rely on bronchoscopy for proper positioning. With flexible bronchoscopy, positioning can be reconfirmed after positioning in lateral decubitus position and can be reassessed mid-operation. Also, bronchoscopy can be used for evaluation of unusual airway anatomy, laryngoscopy of the difficult airway, and for guided pulmonary toilet. For all these reasons, flexible bronchoscopy has become routine in thoracic anesthesia and is widely considered crucial for placement of DLTs safely and effectively.[51,52] At present, there are several companies that have introduced a variety of disposable fiberoptic bronchoscopy that eliminate the need for equipment cleaning and maintenance.

Mechanical Ventilation

Although the "pneumothorax problem" was solved by the application of positive pressure to the lungs, the routine use of intermittent positive pressure ventilation was impractical before the development of mechanical ventilation and muscle relaxation. Mechanical ventilators were not routinely used in the OR until the 1960s to 1970s, only after their acceptance in the intensive care unit. Meltzer and Auer used curare in their animal studies of tracheal insufflation, but it was not used as part of general anesthetic in a human until 1942 when Griffith and Johnson used it for an appendectomy.[53] Harroun used curare with nitrous oxide and morphine as a general anesthetic for thoracic surgery, a useful new technique because it included a nonflammable agent that permitted the use of electrocautery.[54] Curare was soon replaced by safer neuromuscular agents, and neuromuscular blockade became a routine component of general anesthesia. Muscle relaxants facilitate the use of controlled ventilation by suppressing spontaneous respiratory efforts, essentially replacing the hyperventilation method that was used in the past.

Examples of early ventilators have already been mentioned here, such as the Fell-O'Dwyer apparatus from 1892, and Matas' modification of the Fell-O'Dwyer apparatus into a primitive anesthesia machine by incorporating manometry and the delivery of inhalational anesthesia. Innovations by Scandinavian surgeons and anesthesiologists bridged the gap between these early ventilators and the modern ones. Giertz, the student of Sauerbruch's who proved the superiority of intermittent ventilation over constant tracheal insufflation, inspired Frenckner, a Swedish otolaryngologist, to develop the "Spiropulsator" in 1934 for intermittent inflation of the lungs. Frenckner's colleague, Crafoord, included a reservoir bag to permit spontaneous respirations, to prevent the patient from "fighting" the ventilator because muscle relaxation was not yet available.[55] After intubation under local anesthesia, Crafoord and Frenckner's patients were ventilated by the "Spiropulsator" during thoracic surgery. Use of this ventilator was common in Scandinavia, but there was limited interest in controlled ventilation elsewhere in the 1930s and 1940s (Fig. 1.5).



• **Fig. 1.5** The Frenckner Spiropulsator (1934). Note the endotracheal tube with cuff lying to the right. (From Mushin WW, Rendell-Baker L, eds. *The Principles of Thoracic Anesthesia*. Springfield, IL: Charles C Thomas; 1953. Copyright Wiley-Blackwell.)

In 1952, an epidemic of poliomyelitis in Copenhagen inundated Blegdam's hospital where 3000 patients presented with polio, one-third of them presented with paralysis. Faced with so many patients in need of respiratory support, the hospital sought help from Bjorn Ibsen, an anesthesiologist. Ibsen advocated for performing tracheostomies and providing controlled ventilation to weak children to increase their survival.[56] At first the hospital had few mechanical ventilators, so medical students squeezed breathing bags in shifts until more ventilators were acquired. Ibsen's aggressive treatment was a success; survival rates increased dramatically, and the modern intensive care unit was born and the iron lung abandoned. Once the ventilator could be used inside and outside the OR, postoperative ventilatory support was inevitable. In 1955, Björk and Engstrom used postoperative mechanical ventilation for their frailest thoracic surgical patients.[57] After acceptance outside the OR, mechanical ventilators finally gained acceptance in ORs in the 1960s.

Improvements in Intraoperative Monitoring

Complex intraoperative patient monitors are ubiquitous today and mandated by the American Society of Anesthesiologists; however, before the 1960s, intraoperative monitoring consisted of merely observation of color, palpation, and auscultation. An anesthesiologist had only a blood pressure cuff, electrocardiogram, and esophageal stethoscope to rely on. Hypoxemia was only detected by the presence of peripheral cyanosis, frequently, a late, subjective, and unreliable sign. Although the development of accurate invasive monitoring of peripheral arterial, pulmonary arterial, and central venous pressures have helped guide care in the OR, it is the development of noninvasive monitors of oxygenation and ventilation that have become crucial elements of providing safe anesthesia for all types of surgery, and for OLV especially. In 1942, Glen Millikan developed the first oximeter for the ear, intended for use by pilots in World War II to warn them of hypoxia from an oxygen supply failure. In 1972, Takuo Aoyagi, a Japanese engineer, invented the first pulse oximeter that could measure pulse in addition to oximetry.[58] Pulse oximetry gained acceptance in the ORs in the 1980s. Severinghaus declared, "Pulse oximetry is arguably the most important technologic advance ever made in monitoring the well-being and safety of patients during anesthesia, recovery and critical care."[59] Needless to say, pulse oximetry has become the most important monitoring device during OLV. The recognition of potential hypoxemia caused by the transpulmonary shunt can be closely and continuously monitored.

The history of capnography mirrors the development of pulse oximetry. The initial application of infrared absorption to measure expired carbon dioxide occurred in 1943, but capnography was not used widely intraoperatively until the 1980s.[60] It practically eliminated the incidence of accidental esophageal intubation. With good noninvasive monitors of oxygenation and ventilation, the need for the direct measurement of arterial blood gases has decreased but has not been eliminated. Both provide rapid and continuous guides to gas exchange and help guide when direct blood gas measurements are needed.

Additional monitors continue to be developed. With the declining popularity of pulmonary catheters, several noninvasive methods for assessing cardiac output have been developed using a variety of techniques: transthoracic bioimpedance monitors, esophageal dopplers, and monitors of arterial pulse wave analysis. Each of these techniques has its own limitations, and only time will tell whether they will gain popularity for monitoring the thoracic surgical patient.

Improvements in Ventilation

In 1956, halothane was introduced in England, and it rapidly replaced ether and cyclopropane for several reasons. Its favorable safety profile, high potency, less noxious odor, nonflammability, and favorable kinetics with rapid induction and emergence made it preferable to its predecessors.[61] Halothane's potency eliminated the need for supplemental nitrous oxide during OLV. Without nitrous oxide, hypoxemia was less likely. Because of halothane's ability to cause hepatotoxicity and cardiac arrhythmias, it has largely been replaced by newer potent volatile agents, such as isoflurane, sevoflurane, and desflurane. The practices of using potent inhaled agents without nitrous oxide remains common during OLV.

Even with 100% oxygen delivery during OLV, hypoxemia was still common because of blood shunted through the nonventilated lung. CPAP and PEEP are two ventilatory maneuvers for respiratory support outside the OR, and have both been applied to improve oxygenation in OLV. In 1971, CPAP was first described for use in infants with idiopathic respiratory distress syndrome.[62] CPAP can be applied to the nonventilated lung to improve oxygenation by apneic oxygenation, and it has been used for this purpose since the 1980s. Its limitation is that it may interfere with surgical exposure, so it has a limited use during thoracoscopic procedures.[63] PEEP is typically applied to the ventilated lung to improve oxygenation and to prevent atelectasis during OLV.[64] High-frequency jet ventilation (HFJV) with oxygen to the nondependent lung has also been used during OLV to improve oxygenation.[65] HFJV uses a jet of fresh gas delivered from a high-pressure source into the airway at a high rate (100–150 breaths per minute) either through a small catheter or a rigid bronchoscope. Because the tidal volumes are so small, the lung remains collapsed in the surgical field. HFJV is useful in many situations, such as ventilating patients with bronchopleural fistulas, for patients with tracheal stenosis, or for those undergoing tracheal surgery. Today, the use of HFJV has extended outside of the OR, finding a role in procedures where minimization of chest wall movement is desirable, such as cardiac ablations, stereotactic tumor ablations, and extracorporeal shockwave lithotripsy.[66]

Development of Postoperative Analgesia

Advances in pain management have improved care for patients undergoing thoracic surgery. Severe pain results from thoracotomy incisions, and postthoracotomy pain has a profound impact on recovery after surgery by interfering with the return of pulmonary function. Also, inadequate treatment of acute pain following thoracic surgery can contribute to the development of disabling chronic pain. Awareness by anesthesiologists and thoracic surgeons of the impact of inadequately managed acute pain on morbidity has sparked the development of multiple modalities of pain management. Before the 1980s, the only option for patients was systemic opioids, frequently administered intramuscularly. Today, options include systemic opioids, nonopioid analgesics, regional nerve blocks, and epidural local anesthesia and epidural opioids. All can be delivered using patient-controlled analgesia. Recently, emphasis has steered toward nonopioid analgesics and nonepidural regional anesthesia to try to optimize postoperative analgesia but minimize side effects. Between the variety of pharmacologic agents available and the possibility of multimodal analgesia, the options for patients are numerous, and analgesic regimens can be individually tailored to patient needs.

The introduction of neuraxial opioids to the analgesic armamentarium was an early improvement in regional anesthesia. Thoracic epidural analgesia had been attempted for postthoracotomy pain, but when limited to local anesthetics, hypotension was frequently encountered, so this method was not considered viable for routine use.[67] The first advocate for the use of neuraxial opioids was Rudolf Matas himself, who, in 1900, combined morphine with cocaine for spinal anesthesia to reduce the excitatory effect on the central nervous system caused by cocaine.[68] Interest in neuraxial opioid use remained dormant until the 1970s. In 1979, Behar et al., first described the use of epidural morphine for the treatment of pain, and noted its long duration of action.[69] Numerous studies have demonstrated the advantages of epidural over intravenous opioid analgesia. Because of this, thoracic epidural analgesia using opioids combined with low dose local anesthetics became the gold standard for postthoracotomy patients, and the use of epidural catheters for postoperative pain management has contributed to the development of acute pain services and expanded the perioperative role of anesthesiologists.[70,71] The trend of less invasive surgical techniques are currently frequently used, therefore, there has been a focus on less invasive analgesia. Paravertebral blockade has received attention as an alternative to thoracic epidural analgesia. Many studies have demonstrated the analgesic equivalence between the two techniques, whereas paravertebral blocks consistently have fewer side effects.[72]

However, although paravertebral blockade has become a popular alternative to thoracic epidural analgesia, it is still a deep block with many of the same limitations and contraindications as neuraxial blockade, with the added risk of pneumothorax. This has ushered a new interest in fascial plane blocks that are easier to perform with good efficacy and an improved safety profile. Routine use of ultrasound for regional anesthesia has helped spur the development of these fascial plane blocks. Fascial plane blocks that have been used for thoracic surgery include serratus anterior, erector spinae, and pectoralis blocks. Further investigation is warranted, however, studies have suggested that serratus anterior blockade provides improved analgesia for patients undergoing both thoracotomy and video-assisted thoracoscopic surgery (VATS), and may be comparable to paravertebral blockade in certain situations.[73–75] Evidence for the efficacy of erector spinae blockade for thoracic surgery is still limited to case studies and small trials; however, the majority of reports indicate that it is effective with a low risk of complications.[76] Pectoralis blocks are less applicable for thoracic surgery than for breast surgery, however, they have been used as an adjuvant to other analgesic modalities.[77] Intercostal blocks can also be performed before or after thoracic procedures for postoperative analgesia, often performed by the surgeon from within the thorax. These regional block modalities are gaining new interest for the procedures that are performed tubeless with the spontaneously breathing patient.

Broadened Horizons: The Current Scope of Anesthesia for Thoracic Surgery

Thoracic surgical procedures have increased in both number and complexity, and the increased quality and diversity of anesthetic methods for caring for these patients has contributed to this development. Lung cancer continues to be a major public health problem, with 228,150 estimated new cases of lung cancer in the United States in 2019.[78] Since the development of antibiotics, malignancy has been the most common indication for pulmonary surgery. However, important procedures for nonmalignant disease, such as lung transplantation and lung volume reduction surgery (LVRS), are now performed routinely at academic centers, thus making the frailest patients surgical candidates. Lung transplantation has increased from 33 transplants performed in the United States in 1988 to 2501 in 2019.[79] The most common indications for transplantation are severe chronic obstructive respiratory disease (COPD), followed by idiopathic pulmonary fibrosis, cystic fibrosis, alpha 1-antitrypsin deficiency, and primary pulmonary hypertension. LVRS is an option for patients with COPD to try and decrease the frequency and severity of debilitating symptoms; however, the surgery remains controversial because of the high cost of the surgery and rehabilitation, limited improvement, and the high morbidity and mortality postoperatively. Alternative, nonsurgical approaches includes Endoscopic lung volume reduction which encompasses endobronchial insertion of bronchial valves, injection of tissue fibrin glue, endobronchial stents insertion, or coils insertion are nonsurgical approaches to treat end stage emphysema.

Progress in surgical treatment of patients with such compromised pulmonary function has increased the need for anesthesiologists to be involved as perioperative and pain physicians, in addition to their role intraoperatively. Careful preoperative evaluation of patients for thoracic surgery is crucial so that anesthetic management can be tailored appropriately, and that often includes making appropriate plans for postoperative management. Anesthesiologists are increasingly involved in pain management, as well as management of the sickest patients who require intensive care unit stays postoperatively. Because of the variety of roles anesthesiologists fill when caring for patients undergoing thoracic surgery, care for these patients exemplifies the expanded role of anesthesiologists as perioperative physicians.

As the major hurdles of providing safe and effective thoracic anesthesia have been overcome, anesthesiologists are now able to better refine their anesthetic management with the goal of improving short- and long-term outcomes. The development of enhanced recovery after surgery (ERAS) protocols for thoracic surgery is another example of the expanded role of the anesthesiologist in optimizing all phases of care. In ERAS protocols, emphasis includes not only intraoperative management, but also preoperative optimization, postoperative pain management, and anesthetic implications for postoperative recovery, healing, and outcomes. ERAS protocols, already well established in other surgical specialties, aim to reduce postoperative complications and facilitate faster recovery through multidisciplinary implementation of multiple evidence-based measures.

ERAS guidelines for thoracic surgery typically include measures for the prevention of acute lung injury. As the anesthetic management of OLV has improved, the incidence of intraoperative hypoxemia during OLV has dramatically decreased; however, despite improvements in surgical mortality, the rate of acute lung injury was not accompanied by a similar improvement. The ideal ventilation strategy for OLV continues to be controversial, but common components of protective lung ventilation strategies, which most practitioners agree, are low tidal volumes, the use of PEEP, and recruitment maneuvers to limit the parenchymal damage and mitigate the proinflammatory effects of mechanical ventilation. In the past, applying tidal volumes up to 10 to 12 mL/kg during OLV to compensate for the nonventilated lung used to be a common practice. Current understanding of the risks of large tidal volumes favor the use of smaller tidal volumes in the range of 5 to 6 mL/kg.[80] Optimizing fraction of inspired oxygen (FiO2) is another area of interest. It was once standard to use 100% FiO2 for all patients undergoing thoracic surgery. Since hypoxemia has become more preventable during OLV, there has been more interest in decreasing FiO2 levels, with research suggesting that high FiO2 levels may result in more arrhythmia, respiratory failure, and pulmonary hypertension.[81]

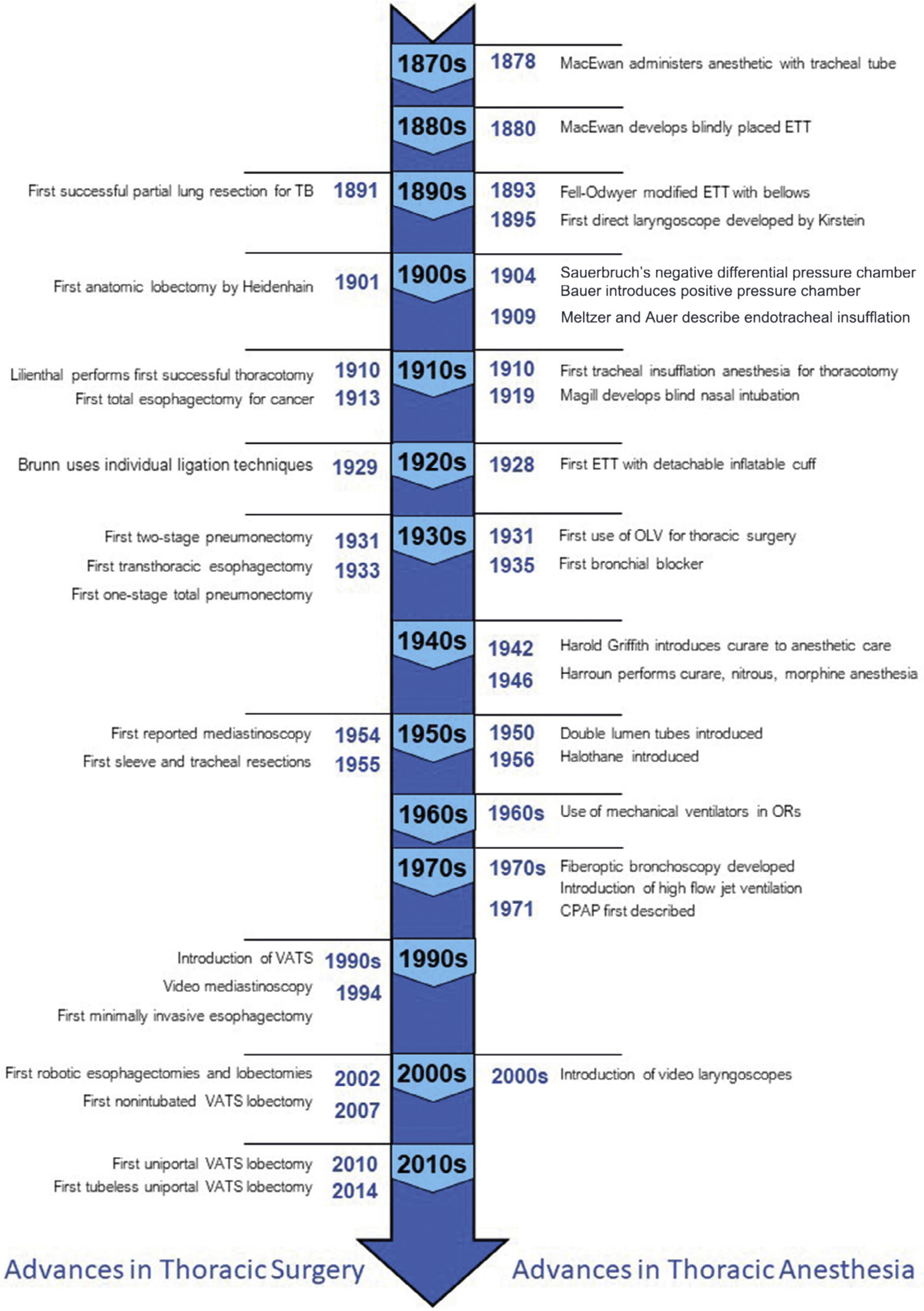
There has been longstanding debate about the merits of volatile versus total intravenous anesthesia in thoracic surgery. Although some studies have shown a protective role of volatile anesthetics on the proinflammatory effects of surgery, others have shown no difference between propofol and volatile agents in major postoperative complications.[82–84] There has also been growing interest in the effect of anesthetic management on tumor recurrence, which is thought to be mediated in part by anesthetic modulation of immune response. For example, limited preclinical studies have reported that propofol may help antitumor activation of T-helper cells.[85] Also, because mu opioid receptors exist on lung cancer cells, the use of opioids may promote lung cancer progression.[86] Regional anesthesia may be protective against cancer recurrence, also through immune modulation. At the present time, to conclusively assess the impact of these anesthetic factors on cancer progression will require more research and no clear recommendations can be offered.

A major advance in thoracic surgery has been the development of minimally invasive techniques. The success of laparoscopy for minimally invasive abdominal surgery in the 1980s, alongside improvements in endoscopic video systems and instruments, spurred thoracic surgeons to develop minimally invasive techniques of their own procedures. VATS has been widely performed since the early 1990s and is increasingly replacing traditional open approaches for more complex procedures. VATS requires optimum lung separation with OLV for adequate surgical exposure because retraction of the operative lung by the surgeon is limited. The benefits of VATS over open techniques include less postoperative pain and shorter hospital stays with faster recovery of preoperative function and increased patient satisfaction.[87] The increase in patient demand for minimally invasive surgery forces surgeons to become more agile with these techniques. Available data confirm that the survival rate following VATS lobectomy for early-stage lung cancer is equivalent to an open thoracotomy.[88] Minimally invasive esophagectomies and mediastinal procedures are routinely performed by VATS. Improvements in camera technology and new, specialized instruments have allowed surgeons to push the boundaries of traditional VATS procedures and begin performing uniportal surgeries. Robotic-assisted techniques for thoracic procedures are also increasingly common, but the benefits and utility of these minimally invasive techniques need to be further defined (Fig. 1.6).

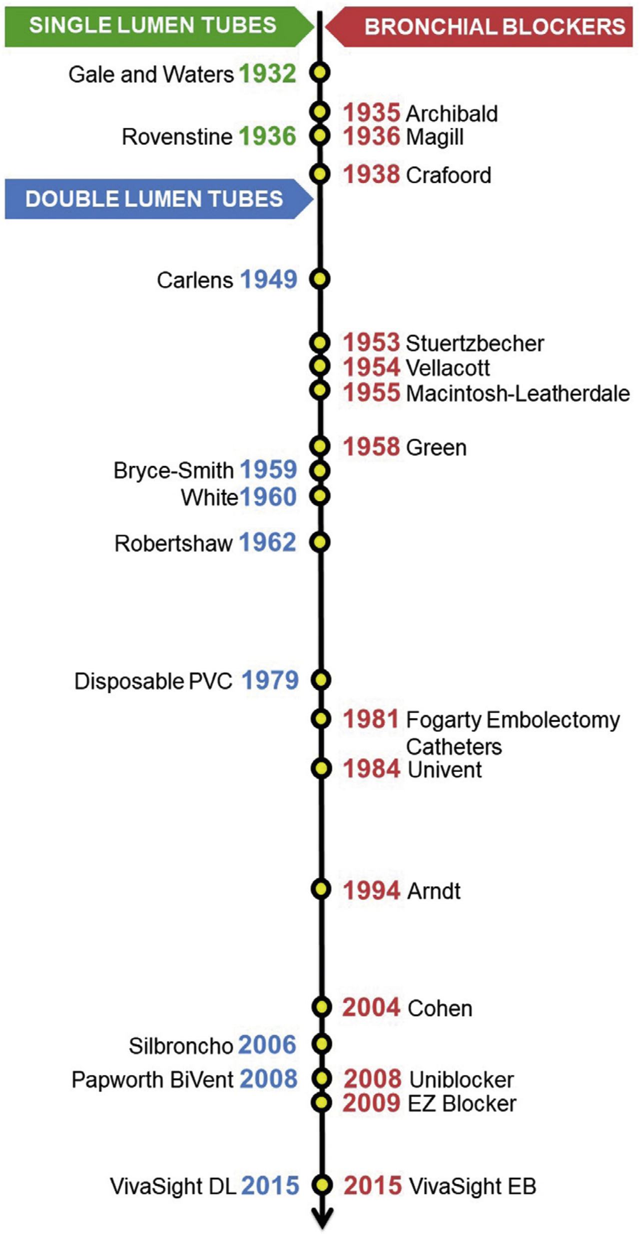
All of these minimally invasive surgical techniques rely heavily on OLV, thus spurring the development of new techniques for lung separation, especially the proliferation of bronchial blockers. The Arndt blocker (Cook Critical Care, Bloomington, IN), introduced in 1994, is wire-enabled and requires coaxial placement for fiberoptic bronchoscopic guided placement. In 2004, the Cohen Tip Deflecting Endobronchial Blocker (Cook Critical Care) was introduced. It possesses a rotating wheel for flexing the tip of the blocker and can be placed under either coaxial or parallel bronchoscopic guidance. Fuji Systems now also manufactures a bronchial blocker, the Uniblocker that is essentially the bronchial blocker from the Univent tube sold separately. The EZ blocker (EZ blocker bv, Rotterdam, The Netherlands) has a novel design featuring a bifurcated distal end that allows for alternating lung isolation and can be positioned without the need of fiberoptic bronchoscopy. The newest developments in the management of bronchial blockers include the VivaSight SL (Ambu Inc Columbia, MO USA) single lumen tube with a distal camera that allows for a bronchial blocker to be placed under direct vision without the need for flexible bronchoscopy.[89]

The search for the ideal DLT continues to be refined. At least five different manufacturers now produce DLTs for either the right or the left bronchus in a variety of sizes. The Silbroncho, is a left-sided DLT made of silicone rubber with a wire-reinforced tip. Proposed advantages of the Silbroncho include a smaller cuff to prevent left upper lobe occlusion, and the flexible, reinforced tip is intended to prevent bronchial lumen kinking or occlusion from compression.[90] The VivaSight DL, similar to the single lumen and bronchial blocker version, offers a high-resolution camera at the end of the tracheal lumen for confirmation of placement by providing a real-time view of the tube at the carinal level and reduces the need for flexible bronchoscopy. It may be useful in cases where the anesthesiologist is away from the patient's head and continued view of the correct position of the DLT is helpful (Fig. 1.7).

Improvement in video technology has resulted in the proliferation of new video integrated airway devices. Flexible video bronchoscopes, which continue to improve in image quality and resolution, are now available as single-use disposable devices by several companies in an effort to decrease the cost and the maintenance associated with reusable scopes. In many situations, video laryngoscopy has replaced flexible bronchoscopy for intubation of the difficult airway, and has been adopted for use for placement of DLTs. Video laryngoscopy allows the patient's airway to be secured from



• **Fig. 1.6** Milestones in the development of thoracic surgery and anesthesia. *CPAP*, Continuous positive airway pressure; *ETT*, Endotracheal tube; *OLV*, One-lung ventilation; *OR*, operating room; *VATS*, video-assisted thoracoscopic surgery.



• **Fig. 1.7** Developments in the history of lung separation techniques. *PVC*: Polyvinyl chloride.

a greater distance, potentially decreasing the spread of infection. For this reason, video laryngoscopy has been widely used during the COVID-19 pandemic.

With the array of bronchial blockers and DLTs now available, providing OLV is easier, safer, and more versatile than ever. Today, single lumen endotracheal tubes are only rarely used for OLV for adults because of the availability of DLTs and the variety of endobronchial blockers that are better suited for lung separation. However, they are still used frequently for children because the relatively small airways of infants and small children cannot accommodate DLTs. The smallest size DLT is 28F that can accommodate adolescent patients. For the pediatric patients that can be managed by 5.0F, the Arndt (Cook Medical, Bloomington IN) or Uniblocker (Fuji Medical, Japan) endobronchial blocker is available. The proliferation of tools and techniques for OLV has also been spurred by increased use of thoracic approaches to spinal, cardiac, esophageal, and vascular procedures. Robotic-assisted techniques for cardiac surgery, including robotic mitral valve repairs, atrial septal defect repairs, and pericardial procedures increasingly use OLV.[91] Such a wide range of procedures requiring OLV has made facility with these techniques a necessity for most anesthesiologists because these surgical techniques may not be possible without adequate lung separation for exposure.

Today, the reliance on OLV has been put to the challenge with the introduction of tubeless thoracic surgery. The definition of tubeless surgery can range from avoidance of endotracheal intubation to the avoidance of all catheters and tubes, including chest tubes and urinary catheters. The procedures are performed with a spontaneously ventilating patient or with an airway laryngeal mask (LMA) or under regional anesthesia. The cough reflex, which was once a hindrance to thoracic surgeons before the invention of endotracheal tubes and muscle relaxation is blunted by aerosolized lidocaine or nerve block. Combining multiple novel minimally invasive techniques, the first uniportal VATS lobectomy was performed on a nonintubated patient in 2014, recalling regional anesthesia used for open thoracic anesthesia in the first half of the 20th century.[92] As thoracic surgery advances, we have started to see echoes of the past, with new technologies and techniques overcoming the problems that made the procedures so dangerous in the past complemented by a return to older techniques. Certainly, history is repeating itself!

Anesthesiologists are also frequently involved in other types of thoracic procedures. Tumors of the bronchi and trachea are frequently treated with stents and/or laser therapy. Airway stenting to palliate patients with severe airway obstructions, usually because of malignant causes, has become increasingly common. These procedures may require special ventilatory techniques, such as HFJV or the Sanders injection system. Also, stents are now frequently placed by interventional pulmonologists outside of the OR, posing unique challenges to the anesthesiologist. When performed under general anesthesia, tracheal resection required cross-field intubation with intermittent ventilation. However, as part of the recent tubeless era, there are recent reports of tracheal resections being performed under regional and neuraxial anesthesia, including cervical epidurals.[93] The improvement in extracorporeal membrane oxygenation (ECMO) technology has made it a more accessible option for these difficult tumors, allowing for better operating conditions, while maintaining oxygenation and hemodynamic support as needed. Novalung, a pumpless lung assistance device can be used to remove carbon dioxide with greater ease, although its oxygenation capacity is poor compared with traditional ECMO.[94]

Anterior mediastinal masses are also particularly challenging for anesthesiologists because of their potential to cause extrinsic compression of the airway and critical obstructions. Patients with anterior mediastinal masses may need anesthesia for diagnostic or therapeutic procedures, and anesthetic management needs to be based on careful preoperative assessment of the potential for airway compression and requires a close collaboration with the thoracic surgeon. As ECMO has become more accessible, precannulation for ECMO is now recommended for those patients at highest risk of cardiovascular and respiratory collapse on induction of anesthesia.

Conclusion

The variety and complexity of procedures now routinely performed by thoracic surgeons would not be possible without the improvements in anesthetic techniques described here. Anesthesiologists over the past 100 years have refined methods of securing the airway, lung isolation, physiologic monitoring, and ventilatory techniques to the point where anesthetizing frail patients for complex procedures appears deceptively easy. Thoracic surgery has flourished with the support of improved anesthesia techniques. The thoracic anesthesiologist of the future will be able to provide the safest anesthesia that will not only facilitate surgery but also optimize short-term recovery and long-term outcomes.

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