The history of anesthesia for thoracic surgery

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ABSTRACT

Today, thoracic surgeons routinely perform complex operations on even the most complicated patient. However, just 75 years ago the ability to operate within the chest was strictly limited to only the simplest and quickest procedures. The dramatic advances in the specialty of thoracic surgery have closely paralleled the introduction of new anesthetic practices, equipment and drugs. This review will identify major events in the history of anesthesia for thoracic surgery.

Key words: History - Thoracic surgical procedures - Anesthesia - Endotracheal intubation - Ventilation, artificial.

The era of modern, safe surgery followed the discovery of inhalation anesthesia in the 1840s. Subsequent advances with general and regional anesthesia techniques and drugs, aseptic surgical practice, fluid and blood transfusions, diagnostic radiography and endoscopy, and improved surgical instruments and operative techniques meant that by 1930 patients could survive most general surgical procedures. This was not the situation for operations in the chest.

Pneumothorax problem

Up until the end of the first third of the 20th Century, the general anesthetic was usually either ether or chloroform administered by mask to a spontaneously breathing patient. This method was acceptable for patients with an intact chest, since respiration was essentially normal during anesthesia. Conditions were different for intrathoracic surgery. Once the surgeon opened the chest wall, the operative lung collapsed and the mediastinum shifted towards the non-operating lung. The patient quickly became tachypneic and cyanotic. The exposed lung would expand and contract in a paradoxical pattern as the patient attempted to breathe, that is, it would become smaller on inspiration and larger on expiration (Figure 1). "Pendulluft" was the term used to describe the transfer of air from the exposed lung to the healthy lung. The thoracic surgeon had only a very short time to complete the operation, since, unless the chest was quickly closed, the patient would die.

This pneumothorax problem was the major hurdle that had to be overcome before procedures more complex than simple chest wall resection or fluid drainage could be attempted. A pioneering surgeon, Matas, succinctly summarized the situation at the turn of the century when he stated "until a solution for lung collapse after opening the chest is solved, an analogy between the pleura and peritoneum from a surgical point of view will never exist".[1]

Two potential solutions to the pneumothorax problem were proposed at a surgical congress in Berlin in 1904.

The first was by Von Mikulicz and Sauerbruch, who placed an animal's body inside a negative-pressure chamber at -15 cm H_2O, while keeping the head outside the chamber. The animal was

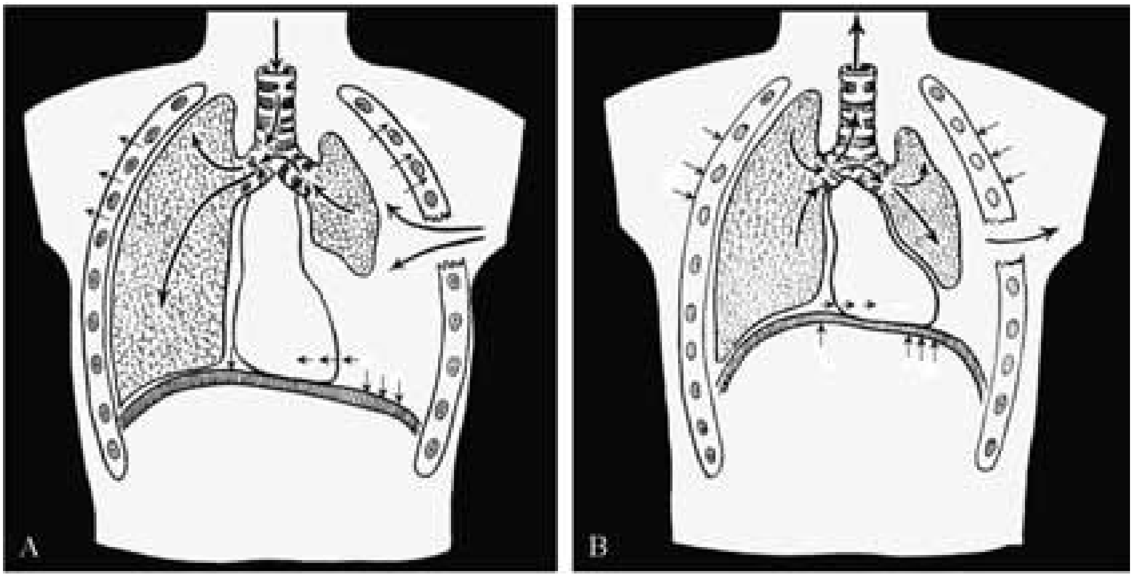

Figure 1.—When the chest is opened, the lung collapses and the mediastinum shifts towards the non-operated lung. As the patient attempts to breathe, the exposed lung expands and contracts in a paradoxical pattern (called "pendulluft"), that is, the lung becomes smaller on inspiration (A) and larger on expiration (B).

Figure 2.—Brauer maintained spontaneous, unassisted, open-chest breathing by placing the patient's head inside a positive-pressure chamber, while the body remained outside the box. The anesthesiologist had no access to the patient's head or airway.

able to maintain lung expansion and continue to breathe unassisted with an open chest.[2] Sauerbruch subsequently performed open thoracotomies on patients placed in a large airtight negative-pressure chamber, with the patient's head and the anesthesiologist located outside the chamber.

The second approach was proposed by Brauer, who was able to maintain spontaneous, unassisted respiration with an open-chest by placing the patient's head inside a positive-pressure chamber, while the rest of the body remained outside of the box.[2] His method was very similar to modern continuous positive airway pressure (CPAP) devices, but the equipment was more complicated and cumbersome (Figure 2). This technique was also used in limited clinical practice, but it was not very practical since oxygenation, carbon dioxide elimination and cardiac filling were usually inadequate and, as with Sauerbruch's chamber, the anesthesiologist had no access to the patient's head and airway.

The major indication for operations within the chest during this time period was pulmonary infection, and neither Sauerbruch's negative pressure chamber nor Brauer's positive pressure chamber protected the healthy lung from contamination by the diseased, operated lung.

TABLE I.—*History of airway management for thoracic surgery.*

Date	Reference	Characteristics
1880	MacEwan	Metal uncuffed tracheal tube
1885	O'Dwyer [3]	Metal uncuffed tracheal tube
1900s	Jackson [4]	Metal laryngoscope for direct intratracheal gas insufflation
1900	Kuhn	Flexible metal trachea tube
1910	Dorrance	Inflatable cuffed endotracheal tube
1920s	Rowbotham/Magill [5, 6]	Uncuffed rubber tube (oral and nasal)
1928	Guedel *et al.*[7]	Cuffed rubber endotracheal tube
1931	Gale *et al.*[8]	Cuffed rubber endotracheal tube inserted into bronchus
1935	Archibald [9]	Rubber endobronchial blocker positioned by radiography
1936	Magill [10]	Rubber endobronchial blocker positioned by endoscopy
1936	Rovenstine [11]	Double-cuffed, single-lumen endobronchial tube
1938	Crafoord [12]	Bronchial blockade with gauze pack
1943	Vernon	Magill blocker with balloon covered with gauze or nylon
1950	Carlens/Bjork [13, 14]	Left double-cuffed, double-lumen endobronchial tube with carinal hook
1953	Sturtzbecher	Endotracheal tube with incorporated catheter and blocker balloon
1954	Vellacott [15]	Right-sided endobronchial tube for right-upper lobe blockade only
1955	Macintosh *et al.*	Left double-cuffed endobronchial tube
1955	Macintosh *et al.*[16]	Cuffed endotracheal tube with incorporated blocker for left blockade
1957	Gordon *et al.*[17]	Right and left double-cuffed endobronchial tube with carinal hook
1958	Pallister [18]	Brompton tube: left endobronchial tube with one tracheal and two bronchial cuffs
1958	Machray	Left endobronchial tube with short bronchial cuff
1958	Green	Similar to Vellacott tube, with carinal hook
1959	Bryce-Smith [19]	Left modified Carlens tube, no carinal hook
1960	White [20]	Right Carlens tube with carinal hook
1960	Bryce-Smith *et al.*[21]	Right Bryce-Smith tube, no carinal hook
1962	Robertshaw [22]	Right and left double-lumen tube with larger lumens and no carinal hook
1979	Burton *et al.* (national catheter) [23]	Plastic right and left Robertshaw design double-lumen tubes
1981	Ginsberg [24]	Fogarty embolectomy catheter for blockade through plastic endotracheal tube
1984	Inoue *et al.*[25]	Univent tube: endotracheal tube incorporating blocker catheter
1990s		Plastic Robertshaw style double-lumen tubes by Mallinkcrodt, Sheridan, Portex and Rusch
1991	Brodsky *et al.*[26]	Modified plastic double-lumen tube for tracheostomies
1994	Arndt *et al.*[27]	Plastic bronchial blocker positioned with wire-snare around bronchoscope
2004	Cohen [28]	Plastic blocker with flexible soft tip to allow control of direction into bronchus
2006	Lohser *et al.*[29]	Silbroncho double-lumen tube: wire reinforced bronchial tip, narrow bronchial cuff

By 1930, each of the individual components needed to solve the pneumothorax problem (direct laryngoscopy, cuffed endotracheal tubes, positive-pressure controlled ventilation) were available and in some cases had been for many years (Table I). Even after each component became widely accepted into anesthetic practice, Sauerbruch's continued advocacy of his negative-pressure method delayed their use in thoracic surgery.[30] Even as late as 1937, Sauerbruch still felt that endotracheal intubation was unnecessary and dangerous.

Positive-pressure ventilation

In Scotland in 1880, MacEwen passed oral tubes into the trachea to relieve upper airway obstruction. Several years later, a pediatrician in New York State, O'Dwyer, developed a practical method of "blind" oral tracheal intubation with a hooked metal airway that he used to treat children with diphtheria[3] (Figure 3). A surgeon in New York, Fell, attached a bellows system to an O'Dwyer intubating cannula to provide positive-pressure ventilation.[30] He used this combined apparatus to treat apneic drug overdose patients.

The combined Fell and O'Dwyer apparatus consisted of a bellows to force air into the lungs, a metal tracheal tube which could be kept in the airway for 24 h or longer, a valve between the bellows and the lungs, a rubber adaptor that prevented injury of the trachea from patient movement and a connecting piece on the tracheal tube that allowed removal and reattachment of tubing to the bellows.

Figure 3.—Fell attached a bellows system to an O'Dwyer cannula (shown) to provide positive-pressure ventilation. The combined Fell-O'Dwyer apparatus consisted of a bellows to force air into the lungs, a metal tracheal tube which could be kept in place for 24 h or longer, a valve between the bellows and the lungs, and tubing between the tracheal tube and bellows. Figure 4.—Matas modified the Fell-O'Dywer apparatus. He inserted a manometer to measure intrapulmonary pressure, and connected a funnel and rubber tubing to the tracheal tube to allow chloroform to be directly administered into the airway.

In 1895, a French surgeon, Tuffier, used a cuffed O'Dwyer tube and rhythmic positive-pressure ventilation for thoracic operations.[31] At about the same time, Matas in New Orleans advocated controlled artificial ventilation *via* a tracheal tube to solve the pneumothorax problem.[32] Matas used the Fell-O'Dwyer apparatus to treat patients with traumatic pneumothorax, and later he applied it in thoracic operations. It would take more than 30 years before his proposal to use artificial respiration for thoracotomy became standard practice and, when it finally did, it revolutionized the field of thoracic surgery.[33]

Initially, Matas used the Fell-O'Dywer system to insufflate air into the lungs. Later, he actively suctioned the tube to remove air during expiration. Through animal experimentation, he realized that aiding the expiratory part of respiration was unnecessary and potentially dangerous. In collaboration with another surgeon, Smythe, he modified the Fell-O'Dywer apparatus to deliver a precise volume of air. He inserted a manometer to measure intrapulmonary pressure, and adapted the intralaryngeal cannula with a port and stopcock connected to a rubber tube and funnel to allow for direct administration of chloroform into the airway [34] (Figure 4).

Although the Fell-O'Dwyer apparatus showed great promise for thoracic surgery and was used in clinical practice by some surgeons, none of its early proponents used direct laryngoscopy to place the tracheal tube. They all relied on the often inaccurate and unhygienic technique of "blind" oral digital placement. Blind tracheal intubation required significant skill and the majority of thoracic surgeons did not feel comfortable or competent using this method.

Laryngoscopy and intra-tracheal insufflation

The principle of direct laryngoscopy was described as early as 1895 by Kirstein who used an "autoscope" to examine the larynx and trachea [35] (Figure 5).[36] Jackson subsequently modified Kirstein's instruments and techniques. The Jackson laryngoscope was used to intubate the trachea under direct vision, and then to deliver an air-ether combination by intratracheal insufflation.[4]

Two American physiologists, Meltzer and Auer, demonstrated in animals that gas blown under pressure into the trachea through a narrow tube could achieve satisfactory gas exchange, but only if the gas was then allowed to escape around the tube.[37] The first successful thoracotomy was credited to Howard Lilienthal at Mount Sinai Hospital in New York City in 1910.[38] For that operation, Elsberg administered an air-ether anesthetic by intratracheal positive-pressure insufflation through a Jackson laryngoscope using Meltzer and Auers' method.[39] The modern practice of oxygen insufflation during rigid bronchoscopy introduced by Sanders in 1968 [40] is very similar to Elsberg's insufflation technique of nearly a century ago. Unfortunately, although laryngoscopy and tracheal placement of the instrument was a prerequisite for intratracheal insufflation, the application of controlled positive-pressure ventilation, which would have solved the pneumothorax problem, was not recognized by these physicians.

Endotracheal tubes

Between 1900 and 1910, Kuhn designed a series of flexible metal tracheal tubes that he placed without the use of endoscopy. During the First World War, the British anesthetists Magill and Rowbotham employed endotracheal anesthesia for max-

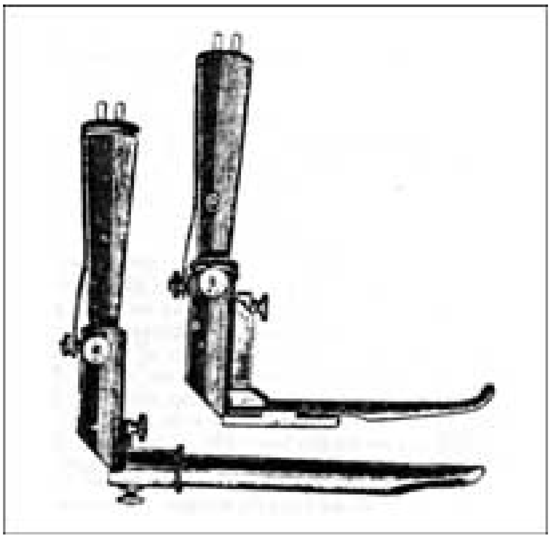

Figure 5.—Kirstein described an "autoscope" in 1895, which he used to examine the larynx and trachea. Jackson subsequently modified Kirstein's instruments and techniques to deliver an air-ether combination by direct intratracheal insufflation.

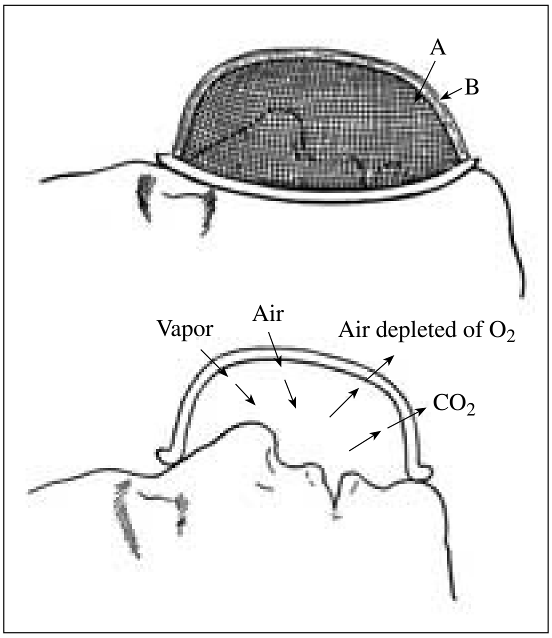

Figure 6.—Ether or chloroform was dropped onto a gauze-covered ether-mask (shown). The spontaneously breathing patient controlled the level of anesthesia. With deeper planes of anesthesia, minute ventilation was reduced so less ether or chloroform was delivered to the lungs and the level of anesthesia was lightened. Since cross-contamination from the diseased to the healthy lung was a potential problem, the level of anesthesia with open drop anesthesia was intentionally kept "light" to allow the patient to maintain protective gag reflexes.

illo-facial surgery. They passed oral and nasal uncuffed, wide-bore rubber tubes into the trachea without laryngoscopy ("blindly").[5, 6] Their technique did not gain widespread acceptance because it required expertise in "blind" tracheal tube placement and because it required deeper levels of anesthesia. Deep levels of anesthesia were associated with loss of protective airway reflexes and, occasionally, cardiovascular collapse.

The most popular general anesthetic technique in the 1920s and early 1930s still remained open drop mask ether or chloroform, a method that had likely not changed for 70 years (Figure 6). The spontaneously breathing patient controlled the actual level of anesthesia. With deeper planes of anesthesia, minute ventilation was reduced so that less ether or chloroform was delivered to the lungs and the level of anesthesia was lightened. Since the usual indication for thoracic surgery was infection and since cross-contamination from the diseased to the healthy lung was always a potential problem, the level of anesthesia with open drop anesthesia was intentionally kept "light" to allow the patient to maintain protective gag reflexes.

Another less popular anesthetic technique consisted of administering oxygen and nitrous oxide through an airtight mask with moderate levels of positive end-expiratory pressure (PEEP) applied to a spontaneously breathing patient. Intravenous morphine was administered for additional analgesia. As with open-drop mask anesthesia, the airway remained at risk for contamination from pulmonary aspiration.

In 1928, Guedel *et al.* attached an inflatable cuff to a rubber endotracheal tube.[7] They were unaware that Dorrance had described a similar tube as early as 1910. Since respirations could be controlled by hand-bag ventilation and since airway secretions could be removed with suctioning through the tube, the depth of general anesthesia could be deepened. The inflated cuff of the Guedel-Waters tube protected the lungs from gastric aspiration. With physician controlled hyperventilation, spontaneous respirations could be eliminated. Deeper levels of anesthesia could be obtained to produce complete diaphragmatic immobility and apnea.[41]

A cuffed endotracheal tube allowing controlled

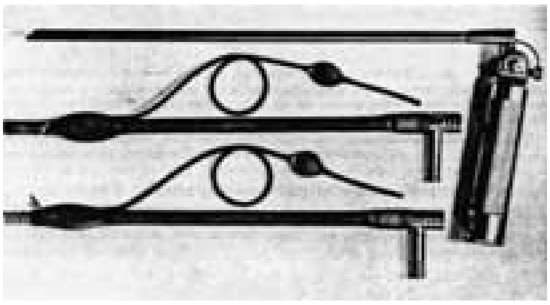

Figure 7.—In 1935, Archibald "blindly" advanced a rubber catheter with an inflatable balloon into the bronchus of the diseased lung for bronchial blockade. Radiographs were used to confirm and readjust the blocker's position. The following year, Magill designed a similar blocker (shown), that could be accurately positioned under direct vision using a rigid endoscope passed down the blocker tube's lumen.

positive-pressure ventilation was the long awaited solution to the pneumothorax problem. The patient was no longer required to breathe spontaneously during open chest procedures. However, even with a cuffed tube in the trachea, cross-contamination from the diseased to the healthy lung was still a significant problem for patients undergoing thoracic operations.

Selective one-lung ventilation

In 1931, only 3 years after the introduction of the cuffed endotracheal tube, Gale *et al.* described an anesthetic technique for selective one-lung ventilation.[8] They used direct laryngoscopy to intubate the patient's trachea with a cuffed rubber endotracheal tube. The tube was then advanced into the bronchus of the healthy lung. When the large volume cuff was inflated, it sealed the intubated bronchus and also extended into the carina where it obstructed ventilation to the diseased lung. The obstructed operated lung collapsed while only the healthy lung was ventilated. The advantages of this technique were an immobile surgical field, quiet respirations, the absence of shock from sudden pneumothorax and, most importantly, protection of the healthy lung from contralateral contamination.

Magill designed a laryngoscope in 1920 for direct placement of rubber tracheal tubes. The modern laryngoscope, described by Flagg in 1932, greatly facilitated placement of endotracheal tubes.[42] The Macintosh laryngoscope blade was introduced in 1943 and is still used today.[43]

These new anesthetic practices allowed the thoracic surgeon to perform operations that had previously not been possible. Surgical advances, such as ligation techniques for airway and vascular structures that reduced the incidence of air leak, tension pneumothorax and hemorrhage, and pleural drainage and postoperative closed chest thoracostomy tubes were introduced during this period. In Germany, Nissen reported the first successful pneumonectomy for bronchiectasis in 1931,[44] and Graham *et al.* reported a total pneumonectomy for a malignancy in 1933.[45] Transthoracic esophagectomy was performed in Japan in 1933.[46] The first report of postoperative pleural drainage for a lung abscess after a pulmonary lobectomy was in 1936.[47]

Bronchial blockade

In 1935, Archibald described bronchial blockade to control secretions during one-lung ventilation.[9] He inserted a rubber catheter with an inflatable distal balloon into the bronchus of the diseased lung using radiographs to confirm and readjust the blocker's position. During surgery, once the balloon was inflated, secretions and blood remained in the diseased bronchus, while lung tissue beyond the inflated balloon collapsed. The healthy lung was ventilated through an endotracheal tube inserted alongside the blocker catheter.

The following year, Magill designed a similar blocker that could be accurately positioned under direct vision with an endoscope that was passed down the blocker tube's lumen[10] (Figure 7). Considerable clinical experience was needed for successful placement of early bronchial blockers. Early blockers were placed many years before muscle relaxants were available, so sudden and violent movements by the patient were not uncommon. The anesthesiologist had to take great care following endotracheal intubation to ensure that the blocker was not displaced. When the balloon was deflated and the blocker withdrawn into the trachea, the healthy lung was no longer protected from soiling by the diseased lung.

In 1936, Rovenstine used a double-cuffed, single-lumen endobronchial tube that he advanced "blindly" into the bronchus of the healthy non-operated lung.[11] When the proximal balloon in the trachea was inflated, both lungs could be ventilated, but when both cuffs were inflated, the distal balloon in the bronchus isolated the healthy lung from the diseased lung, thus allowing ventilation only to the healthy intubated lung.

Anything that blocks a bronchus will cause lung tissue beyond the obstruction to collapse from absorption atelectasis. Many endobronchial tubes and airway tubes combined with bronchial blockers were subsequently introduced into anesthetic practice.[15-18, 48, 49] Crafoord even used a ribbon gauze tampon as a bronchial blocker to control secretions.[12]

A modern derivative of these tubes is the Univent tube, introduced in the 1980s.[25] It is a large endotracheal tube with a small anterior channel that contains a thin, balloon-tipped catheter. This catheter can be advanced into either bronchus under direct vision using a fiberoptic bronchoscope. When inflated, the balloon serves as a bronchial blocker. If postoperative ventilation is planned, tracheal re-intubation is unnecessary since, at the completion of surgery, the blocker catheter can be withdrawn back into the main body of the endotracheal tube, which is then used as a conventional endotracheal tube.

Until recently, balloon-tipped catheters, such as Fogarty embolectomy catheters, pulmonary wedge catheters, and even urinary catheters, all designed and intended for other uses, have been used as bronchial blockers.[24] Plastic tubes specifically designed for bronchial blockade have now become available.

The Arndt blocker employs a wire-loop snare at the tip of the catheter that allows it to be coupled to a pediatric bronchoscope. The bronchoscope and the blocker are advanced into the appropriate bronchus under direct vision through an endotracheal tube. When the blocker balloon is in the correct position, the bronchoscope is withdrawn.[27] Another blocker has a flexible distal tip that can be directed into the bronchus by means of a control mechanism at its proximal end.[28] Both of these catheters are intended only for bronchial blockade. Their balloons have low-pressure properties to reduce the risk of airway trauma.

Bronchial blockade does not permit suctioning, bronchoscopic examination, or re-expansion and re-collapse of the operated lung during surgery. Blood, pus or loose tumor material can collect behind the inflated balloon during surgery, so there is the possibility of cross-contamination when the blocker balloon is deflated and the healthy lung is no longer isolated. Bronchial blockade is particularly useful in situations when placement of a double-lumen tube is impractical or impossible, such as in adults with "difficult" airways or in children whose airways are too small for a double-lumen tube.[50]

Double-lumen tubes

In 1949, Carlens, a clinical physiologist in Stockholm, Sweden, described a double-cuffed, double-lumen tube intended for intubation of the left lung.[13] The tube was intended to be used for differential broncho-spirometry. A double-cuffed double-lumen tube consists of two tubes of unequal length that are molded together. The shorter tube ends in the trachea and the longer tube enters either the left or the right main bronchus. When the proximal cuff on the main body of the tube is inflated, positive-pressure ventilation can be delivered to both lungs. When the distal bronchial cuff is inflated, ventilation can be directed into either or both lungs by selectively clamping gas flow to the tracheal or bronchial lumen at the proximal end of the tube.

In 1950, Bjork *et al.* used the Carlens tube for selective one-lung ventilation during thoracic surgery.[14] The Carlens tube had a hook to engage the carina. This carinal hook was helpful for "blind" placement in the bronchus, but it could cause serious damage to the airway. In 1959, Bryce-Smith described a left sided-double-lumen tube similar to the Carlens tube, but without the carinal hook[19] (Figure 8). The following year, White and Bryce-Smith *et al.* described double-lumen tubes intended for intubation of the right-main bronchus.[20, 21]

During intrathoracic procedures, a double-lumen tube allows safe and effective positive-pressure one-lung ventilation, allows the diseased lung to collapse, thus providing the surgeon with a quiet operative field, and separates each lung. Isolating the lungs protects the dependent healthy lung

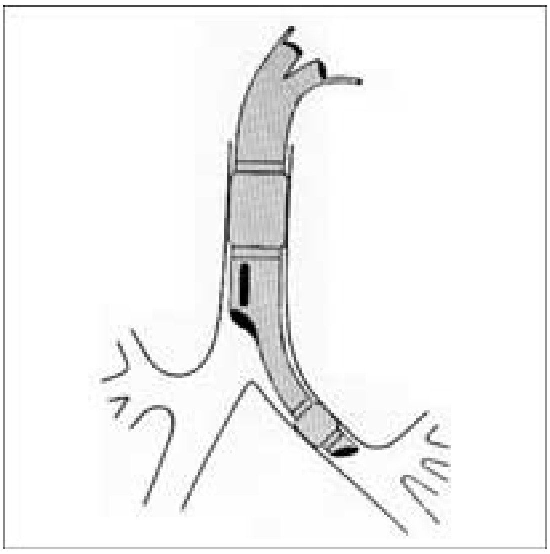

Figure 8.—Carlens described a double-cuffed, double-lumen tube, intended for intubation of the left lung, in 1949. All double-lumen tubes consist of 2 tubes of unequal length that are molded together. The shorter tube ends in the trachea and the longer tube enters either the left or the right main bronchus. When the proximal cuff on the main body of the tube is inflated, positive-pressure ventilation can be delivered to both lungs. When the distal bronchial cuff is inflated, ventilation can be directed into either or both lungs by selectively clamping gas flow to either lumen. The Carlens tube had a hook to engage the carina. This carinal hook helped with "blind" placement, but was a potential cause of airway injury. In 1959, Bryce-Smith described a left sided-tube, similar to the Carlens tube, but without the carinal hook (shown). Bryce-Smith *et al.*, and White subsequently described double-lumen tubes that were intended for intubation of the right-main bronchus.

from aspiration while the patient is in the lateral position.[51, 52] The operated lung can be safely collapsed, re-inflated and re-collapsed at any time during the procedure. The bronchus of the operated lung can be suctioned to remove blood and secretions before the lung is re-expanded, thus reducing the risk of cross-contamination. The bronchus of the operated lung can be visually evaluated with a pediatric bronchoscope.

Difficulty with tracheal intubation and with accurate placement in the bronchus, as well as high airway resistance during one-lung ventilation, initially restricted the clinical use of double-lumen tubes. The Robertshaw tube, introduced in 1962, solved some of these problems.[22] It lacked the carinal hook of the Carlens and White tubes. The rubber Robertshaw tube had wide lumens and a molded curvature to reduce kinking and improve gas flow during one-lung ventilation.

Disposable, plastic double-lumen tubes have been in clinical use since the early 1980s, and have now completely replaced the re-usable rubber double-lumen tubes of earlier times.[23] The plastic material allows greater ease and safety in tracheal intubation and bronchial placement. The walls of plastic tubes are thin so each lumen is larger than the lumens of rubber double-lumen tubes of equivalent circumference. Large lumens offer less resistance to airflow during one-lung ventilation and allow easy passage of a suction catheter or fiberoptic bronchoscope. Moreover, the presence of water vapor, blood and secretions is visible through the clear plastic material. In contrast to the low-volume, high-pressure cuffs of the older rubber tubes, all plastic double-lumen tube cuffs have high-volume, low-pressure properties that reduce the risk of airway trauma.[53]

Today, several different manufacturers offer plastic double-lumen tubes. They are all similar in design to the Robertshaw tube, but each differs in its overall dimensions and in the design of the bronchial cuff. Plastic double-lumen tubes are available for intubation of either the right or left lung in sizes ranging from 26 to 41 Fr.

New tube designs continue to be introduced. Modified shortened double-lumen tubes are available for patients with tracheostomy stomas.[26] The new Silbroncho tube has a wire-reinforced bronchial tip to prevent bronchial lumen compression when the patient is in the lateral position, and it has a very narrow bronchial cuff to reduce the chance of upper-lobe obstruction.[29]

The majority of intrathoracic surgical procedures would be difficult or impossible for the surgeon to perform without a double-lumen tube or bronchial blocker. These devices are easy to place, especially with the aid of a fiberoptic bronchoscope. Lung isolation to protect the healthy lung from spillage and contamination is mandatory in cases of infection or massive hemorrhage. For all procedures within the chest, selective collapse of the operated lung improves operative conditions and thus reduces the duration of surgery. Only a double-lumen tube can be used to control of the distribution of ventilation to either or both lungs during a surgical procedure. Furthermore, whole lung lavage for alveolar proteinosis would not be possible without a double-lumen tube.

Fiber-optic bronchoscopy

Flexible fiberoptic bronchoscopy was introduced into clinical practice the 1970s. Direct examination of the airways greatly aids the diagnosis, staging, and management of lung disease. In the 1980s, fiberoptic bronchoscopes were first used to help position double-lumen tubes.[54] Although double-lumen tubes can be safely be positioned "blindly",[55] the fiberoptic bronchoscope has greatly simplified and improved the accuracy of tube placement for anesthesiologists who only occasionally use double-lumen tubes in their practice. Positioning these tubes under direct vision can reduce the risks of trauma and hypoxemia from malposition. Modern bronchial blockers cannot be positioned without a fiberoptic bronchoscope.

Mechanical ventilation

In 1916, Giertz, a former assistant of Sauerbruch, conducted animal experiments in which he demonstrated that rhythmic inflation of the lungs was more effective for gas exchange than either Sauerbruch's negative pressure chamber or Brauer's positive pressure method. By 1934, Guedel was routinely manually controlling intraoperative ventilation through a cuffed endotracheal tube. The first experimental ventilator, the "Spiropulsator", was described by a Swedish otolaryngologist, Frenckner in 1934, and it was used in surgery shortly afterward by Crafoord.[56]

However, intermittent positive-pressure mechanical ventilation was not practical until muscle relaxants were introduced into clinical anesthetic practice in the 1940s.[57] Neuromuscular blocking drugs allowed easier intraoperative control of ventilation with much lighter planes of general anesthesia. Curare was first used in thoracic surgery in 1947.[58] An anesthetic technique combining curare with oxygen and nitrous oxide and morphine was developed, which allowed unrestricted use of electrocautery during surgery. This significantly reduced the risk of bleeding, which was a major risk during operations for pulmonary infections.

Despite early success in Europe with mechanical, controlled ventilation in paralyzed surgical patients, continuous positive pressure by mask or intratracheal insufflation remained the main technique used for thoracic anesthesia well past the 1940s.

Figure 9.—The Engstrom volume-controlled ventilator (shown) had been successfully used in the management of poliomyelitis victims, and was then applied by Bjork *et al.* for postoperative care of thoracic surgical patients. Their success with this ventilator convinced anesthesiologists that they could be used during surgery. General acceptance of controlled ventilation in the operating room did not occur until 1950s-1960s.

General acceptance of controlled ventilation during operations did not occur until after the polio epidemic in Denmark in 1952. The Engstrom volume-controlled ventilator had been successfully used in the management of poliomyelitis victims. Mechanically controlled ventilation was then applied by Bjork *et al.* in Sweden for postoperative care of thoracic surgical patients[59] (Figure 9). Experience with ventilators outside of the operating room convinced anesthesiologists that these machines could be used during surgery. Routine use of intraoperative mechanical ventilation did not occur until the 1960s.

Anesthetic agents

Until about 50 years ago, the usual choice of anesthetic for thoracotomy was either ether or cyclopropane. Cyclopropane was especially useful because it allowed the anesthesiologist to easily control ventilation.[60] Although ether and cyclopropane were generally safe to administer, they were highly explosive. In 1956, halothane was introduced into clinical practice and it quickly replaced these anesthetic agents.[61] Halothane produced a relatively smooth induction and emergence, was nonflammable, so it could be safely used with electrocautery, and because of its increased potency, the need for nitrous oxide was eliminated which allowed for higher concentrations of oxygen to be administered during one-lung anesthesia. However, halothane was found to be associated with cardiac arrhythmias and liver toxicity. It was replaced by methoxyflurane and enflurane in the 1960-70s. These agents in turn were replaced by isoflurane, sevoflurane, and desflurane, and each of these have been in use since the 1980s or 90s.

Intraoperative monitoring

Prior to the 1960s, intraoperative monitoring was accomplished by an electrocardiogram, cuff blood pressure measurements, and an esophageal stethoscope. The development of invasive monitors during the 1960s-1970s allowed anesthesiologists to accurately measure and manipulate physiologic variables, such as central venous and pulmonary artery pressures, for the first time.[62] Arterial blood gas analysis was used to guide ventilatory management during one-lung ventilation. Today, we depend on safe non-invasive monitors.[63] End-tidal capnography and pulse oximetry have greatly reduced the incidence of adverse intraoperative events, and their application during one-lung ventilation has eliminated the need for invasive monitors for many patients.[64] We may soon have practical methods for continuously measuring oxygenation, ventilation and acid-base balance during surgery. Instruments capable of performing these tasks are currently under clinical investigation.[65]

Maximizing oxygen during one-lung ventilation

Even with controlled ventilation and inspired 100% oxygen, persistent pulmonary blood flow or "shunt" to the non-ventilated operated lung during one-lung ventilation can produce dangerously low blood oxygen tensions. PEEP and CPAP, techniques initially developed for managing patients in respiratory failure, were applied in the 1980s during one-lung ventilation.[66] PEEP to the ventilated lung, CPAP to the collapsed lung, or the combination of both, are used during thoracotomy.[67] The pharmacologic manipulation of pulmonary circulation by selective pulmonary artery vasoconstriction and vasodilation may someday completely eliminate the risk of hypoxemia during one-lung ventilation.[68]

Post-thoracotomy analgesia

The lateral thoracotomy incision is intensely painful and, if inadequately treated, post-thoracotomy pain can lead to postoperative pulmonary dysfunction. Opioid analgesics have traditionally been used to treat this pain. However, the therapeutic window for systemic opioids is narrow, since over-medication will produce hypoventilation, while under-medication will prevent deep breathing and induce coughing. Many analgesic regimens (systemic opioids, spinal and epidural opioids, ketamine, non-steroidal anti-inflammatory drugs, intercostal nerve blocks, cryo-analgesia, trans-electrical nerve stimulation, intrapleural local anesthetics, epidural and paravertebral local anesthetics) are used for post-thoracotomy analgesia.[69, 70]

The greatest modern advance in the treatment of surgical pain has been the use of neuraxial opioid analgesia, alone or combined with local anesthetics. Behar *et al.* reported on the efficacy of epidural morphine for pain management in 1979.[71] Rapid acceptance of neuraxial (intrathecal and epidural) opioid analgesia soon followed.[72] Local anesthetics administered by the spinal and epidural route had previously been used for post-thoracotomy pain, but the high incidence of associated hypotension made these approaches less than ideal.

In Toronto in 1984, Shulman *et al.* performed a prospective study comparing epidural and intravenous morphine for post-thoracotomy analgesia.[73] They reported superior pain relief and improved postoperative pulmonary function in the epidural group. Their results were confirmed by others that analyzed thoracotomy patients.[74] Since then, the use of lumbar and thoracic opioid epidural analgesia, often combined with local anesthetics, has had a major role in the postoperative management of thoracic surgical patients. Many believe that no other treatment modality is superior.[75]

A comfortable, spontaneously breathing patient will have fewer complications and recover more quickly. Advances with pain management are a major reason for the remarkable reduction of morbidity and mortality following thoracic operations over the past 2 decades.

Conclusions

Only the simplest intrathoracic operations were safe or feasible as recently as the 1930s. The introduction of methods for securing the airway, isolating the lungs, and selectively ventilating either or both lungs; the use of invasive and non-invasive physiologic monitoring; and the ability to provide satisfactory post-thoracotomy analgesia have all contributed to the present situation. Today, thoracic surgeons can safely perform complex procedures on the most debilitated patients. The anesthetic management of the thoracic surgical patient has experienced a remarkable evolution. Operations like lung volume reduction or lung transplant would have not have been possible only 30 years ago. Progress in anesthesiology continues, so operations that are unimaginable today may someday become routine.

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