Review Article

Surgery of the airway: historic notes

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Abstract: Prior to the 20th century, the need for surgical procedures on the airway was infrequent and consisted mainly of tracheostomy to relieve airway obstruction or repair of tracheal injuries such as lacerations. Even the ability of tracheal suture lines to heal primarily was viewed with concern due to the rigidity of the tracheal wall, its precarious blood supply and uncertainty as to whether the cartilage components could heal without complications. In the 20th century the evolution of tracheal procedures on major airways evolved to meet the challenges provided by the expanding fields of thoracic surgery and advent of mechanical respiratory support with its associated complications. In the first half of the century lobar and lung resections done for tuberculosis and lung cancer required methods for safe closure of the resulting bronchial stumps and end-to-end bronchial anastomosis in the case of sleeve resections of the lung. Beginning in mid-century the advent of respiratory care units for the treatment of polio and for the expanding fields of thoracic and cardiac surgery resulted in a significant number of post-intubation tracheal stenosis requiring resection and primary repair. In the last 20 years of the century the development of lung transplantation with its requirement for successful bronchial anastomoses between the donor and recipient bronchi, created unique challenges including ischemia of the donor bronchus the adverse effects of immunosuppression, donor lung preservation and diagnosis and management of post-transplant infection and rejection.

Keywords: Tracheal resection; bronchial anastomosis; tracheal bronchial surgery

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Surgery of the airway has its roots in ancient history but its major developments have occurred in the last 60 years.

The oldest recorded surgical procedure on the airway is in the *Edwin Smith Papyrus an ancient Egyptian medical text* thought to date around 1600 BCE. The papyrus is primarily concerned with traumatic injuries and their treatment and demonstrates a procedure thought to be a tracheotomy to provide an emergency airway. References to tracheostomy were also made in the Greek literature and the use of a tube placed through a tracheostomy was noted in the 4th century BCE (1). Until the early part of the last century, surgery of the airway was confined primarily to tracheostomy to relieve upper airway obstruction such as for diphtheria, or for repair of traumatic injuries, such as lacerations, to the trachea. Several authors have chronicled the history and evolution of tracheostomy procedures (1-3).

The advent of elective surgical procedures for the resection and reconstruction of the major airways began in the mid portion of the last century. Progress was hampered by technical and biologic factors peculiar to the airway as well as by infrequent need for such procedures.

In 1881 Glück and Zeller (4) were able to demonstrate healing end-to-end after tracheal anastomosis in dogs and in 1886 Küster successfully performed a primary tracheal anastomosis of the cervical trachea after resecting a segment for post-traumatic stenosis (5). In the early part of the last century animal studies confirmed that end-to-end anastomoses following bronchial or tracheal resection could heal. Human experience with satisfactory bronchial closure after lobectomy or pneumonectomy confirmed the importance of fibrous tissue repair on the outer portion of the airway as an important component in the satisfactory healing of wounds, incisions and anastomoses of the airway. Success in repair of war-time injuries to the bronchus in World War II (6) and subsequent successful end-to-end bronchial anastomoses for sleeve lobectomies (7) confirmed the potential for satisfactory healing following anastomosis of the major airways (7-9).

Belsey, in a manuscript entitled "Resection and Reconstruction of the Intrathoracic Trachea" in 1950, observed that "the intrathoracic portion of the trachea is the last unpaired organ in the body to fall to the surgeon, and the successful solution of the problem of its reconstruction may mark the end of the 'expansionist epoch' in the development of surgery" (10). Belsey noted that among factors inhibiting successful surgical procedures on the trachea were centuries-old concerns regarding the poor-healing properties of the trachea. These admonitions related to poor blood supply, rigidity of the cartilaginous rings which interfered with easy, tension free apposition of wound edges, and the technical difficulties of operating on the trachea without suspending its essential role of providing a conduit for ventilation of the lungs. Belsey noted the absence of a satisfactory means of surgically bypassing portions of the trachea contrary to methods of bypassing other conduits such as the bowel and blood vessels. He also postulated that if trachea replacement were to be possible, a substitute would require a laterally rigid but longitudinally flexible tube and would ideally have an inner surface of ciliated respiratory epithelium.

By the mid-1950s it was well established that closure of bronchial stumps following lobectomy, and end-to-end bronchial anastomoses and broncho-plastic procedures for lung preserving pulmonary resections could be performed with good results, as reported by Paulson and Shaw in 1955 (11). However there was still a perception that only very limited lengths of trachea could be resected with primary anastomosis (4,12). Concerns related to the ability of tracheal cartilage to heal, the adverse effects of anastomotic tension on anastomotic healing and the tenuous blood supply to the trachea. In addition, in the 1950s, the indications for a tracheal resection were limited, consisting mainly of tracheal tumors which were often deemed unresectable, or which would require a resection length greater than the widely perceived 2 cm limit for safe tracheal resection. Furthermore at that time the anesthetic techniques for conducting intrathoracic resection of the trachea while maintaining adequate ventilation were not well-developed. Thus the stimulus for expanding the techniques and limits of tracheal resection was lacking. All of that was to soon change however due to the worldwide epidemic of poliomyelitis in the early 1950s which initiated the era of positive pressure ventilation through cuffed endotracheal or tracheostomy tubes. Over the ensuing decade respiratory intensive care units were initiated, initially for ventilatory assistance for patients with neurologic disorders, such as Polio, Myasthenia Gravis, Guillain Barre Syndrome, strokes, etc. The burgeoning of thoracic surgery and cardiac surgery expanded the need for postoperative positive pressure ventilation and this experience in turn further stimulated progress in anesthetic techniques, the development of more sophisticated ventilators, the field of respiratory therapy and the routine application of ventilatory assistance in specialized medical and surgical intensive care units. In the mid-1960s however, the hospital mortality rate for patients requiring ventilatory assistance was between 30–50%. Furthermore, amongst the survivors 20% or more developed airway complications, primarily tracheal stenosis. This situation set the stage for investigation and clinical application of techniques to extend the safe limits of tracheal resection. Cadaveric studies were undertaken to elucidate the blood supply of the trachea, and demonstrated the lateral position of the arterial supply which in turn fed the small segmental vessels to the trachea (13,14). Mobilization techniques to reduce anastomotic tension focused on the arterial anatomy and included anterior and posterior blunt mobilization of the trachea down to the carina augmented by the inherent elasticity of the trachea itself. Mobilization of the carina by means of right hilar dissection and division of the right pulmonary ligament, and laryngeal release at the upper end of the trachea further extended the limits of safe tracheal resection. Dedo and Fishman, in 1969 described the thyro-hyroid laryngeal release as an adjunct to resections for tracheal stenosis (15). In 1974 Montgomery described the suprahyoid release, which is now the most widely accepted form of laryngeal release in terms of efficacy, reduced morbidity and technical simplicity (16).

A cadaver study by Mulliken and Grillo, reported in 1968, demonstrated that the combination of cervical and mediastinal mobilization of the trachea, together with flexion of the neck by 15 to 35 degrees, resulted in an average of 4.5 cm of trachea that could be resected with end-to-end approximation with no more than 1,200 grams of tension applied to the divided ends of the trachea (17). The addition of right hilar dissection and intrapericardial mobilization at the lower end, and laryngeal release at the upper end, could facilitate even more aggressive resection.

Between 1965 and 1971 a series containing a large numbers of tracheal resections were reported, most for post-intubation tracheal stenosis (13,18-28). This in turn focused attention on the need to prevent such post-intubation injuries.

In 1965 the author (Cooper) was a surgical resident at the Massachusetts General Hospital, where Dr. Hermes Grillo was director of the general surgery training program. At his suggestion and with his guidance, an autopsy study was undertaken whereby patients dying while receiving ventilatory assistance would have the existing tracheostomy or endotracheal tube secured in place for the subsequent autopsy dissection, contrary to the usual custom at the time of removing all tubes and catheters prior to sending the deceased patient for autopsy. This permitted excision of the larynx and entire trachea with the tube in place allowing correlation between the tip of the tube, the location of the cuff etc., with any underlying adjacent changes observed in the airway. For the 30 post-mortem examinations so conducted, the duration of intubation ranged from 1 to 60 days. A spectrum of lesions were seen at the cuff site with superficial tracheitis and mucosal ulceration apparent after a few days of intubation followed by exposure and infection of cartilaginous rings after a few more days. The final stage of cuff injury included fragmentation and loss of cartilage resulting in an unsupported, ulcerated and inflamed segment of trachea. It was presumed that the subsequent development of tracheal stenosis in survivors of ventilatory assistance was due to cicatricial scarring and constriction of this damaged unsupported segment (29). Other reports also pointed to tracheal injury at the cuff site as a possible cause of tracheal stenosis (30) including a prospective bronchoscopic evaluation of 103 patients receiving ventilator support conducted by Andrews and Pearson (31). The exact cause of this localized damage at the cuff site however had not been determined and was variably attributed to the nature of the cuff material, the exposure of the cuff to gas sterilization prior to its use, infection and pressure necrosis. In the previously noted autopsy study reported by Cooper & Grillo, the intracuff pressure necessary to inflate the cuff on the endotracheal tube or tracheostomy tube to an occlusive volume was measured and was in the range of 200 mm of mercury. Such high intracuff pressure is primarily related to the force required to distend the cuff, and not necessarily to the pressure applied to the adjacent tracheal mucosal. The intracuff pressure, however, does correlate with the rigidity of the inflated cuff and the resulting pressure it places on the adjacent trachea, which has to conform to the shape of the cuff to create a seal. However with a large volume, low pressure cuff, the cuff is easily deformed and adapts its shape to that of the adjacent trachea creating a seal with very little force on the trachea itself. In 1943, Grimm & Knight had suggested that an ideal intra-tracheal tube cuff "should have sufficient volume when inflated without stretching to fill the diameter of the trachea" (32).

On the basis of the findings of their autopsy study, Cooper and Grillo designed an experimental canine model to compare the effect of the standard cuffs with that of a large volume, thin walled, latex cuff. Each cuff was mounted on a segment of an endotracheal tube and implanted in a dog's trachea. The cuff was kept inflated to produce an airway seal between the cuff and the trachea at an airway pressure of 20 cm of water. After a week of exposure the low pressure cuff produced no mucosal damage, compared to the use of the standard, elastic, high pressure cuff then in use, which resulted in the same type of ulceration, cartilaginous fragmentation, and loss of tracheal support, observed in the human post mortem studies (33). A subsequent randomized clinical trial comparing experimental low pressure tracheostomy tube cuffs with the standard cuffs confirmed the role of pressure necrosis at the cuff site caused by the standard cuff and the absence or marked reduction in tracheal injury with the low pressure cuff.

A second type of post-intubation tracheal stenosis relates to damage at tracheostomy stomal site. Stenosis at this site is due to the loss of the anterior supporting arch of the tracheal rings with subsequent inward collapse of the lateral tracheal walls, resulting in the so-called "A-frame" deformity. Unlike circumferential strictures at the cuff site, stomal strictures involve scarring and narrowing only on the anterior wall of the trachea at the stomal site whereas the lateral and membranous walls remain mobile. This generally results in preservation of the A–P dimensions of the trachea, with marked side to side narrowing. This situation may not produce symptoms for even decades. During this interval the anterior wall angulation may act as a hinge allowing the sidewalls to easily move laterally with respiration. However, with time the lateral walls may become fixed in a more central position leading to symptoms. In a recent case, a 75-year-old man presented with acute, severe stridor and airway obstruction having essentially been asymptomatic for the 70-year interval following a temporary tracheostomy for upper airway obstruction at age 5. The risk of such a stenosis increases with the size of the tracheostomy tube used and may be further augmented by enlargement of the stoma due to traction on the tracheostomy tube by the attached ventilator tubing. With the use of a lightweight, flexible, swivel tracheostomy tube connector between the tracheostomy tube and the ventilator tubing, Andrews and Pearson observed a reduction in the incidence of stomal stenosis from 17.5% to 6.9% (31).

Concurrent with the development of techniques to extend the limits of tracheal resection, increasingly complex resections were developed for tumors involving the carina and main bronchi. A number of reconstruction methods were used depending on the exact extent of tumor involvement of the distal trachea and main bronchi. This included side-to-side anastomosis between the two main bronchi which were then attached end-to-end to the distal trachea; end-to-end anastomosis between the trachea and the left main bronchus with implantation of the right main bronchus into the right lateral aspect of the trachea; end-to-end anastomosis between the trachea and the right main bronchus with attachment of the left main bronchus to the side of the right intermediate bronchus, and others. Such procedures not only present technical challenges, but require close coordination between the surgeon and an experienced anesthesiologist using a variety of techniques including high-frequency jet ventilation, intermittent ventilation and cross-table ventilation with an endotracheal tube placed into one or other main bronchus by the surgeon. In general the use of cardiopulmonary bypass has not been employed out of concern that extensive manipulation of the lung during the anticoagulation required for bypass might lead to parenchymal hemorrhage, pulmonary edema and the need for postoperative ventilatory assistance, which poses a significant risk to patients undergoing any type of airway reconstruction.

Bjork in 1959 (34) reported on a series of bronchotracheal anastomoses and subsequent series of successful carinal resections were reported by Eschapasse in 1974, Perelman in 1980 and Grillo in 1982 (35-37). Several other reports focused on the anesthetic challenges and their management for complex trachea-bronchial reconstructions (38-42).

Just as resections at the distal end of the trachea require more complicated techniques than tracheal resections alone, special techniques were also required for proximal conditions involving the upper end of the airway and the subglottic region. These require resection of the proximal end of the trachea with anastomosis to the larynx for traumatic injuries, damage to the subglottic region from endotracheal tubes and idiopathic subglottic stenosis. Such resections often require an anastomosis within a centimeter of the vocal cords and create a significant risk for damage to one or both recurrent laryngeal nerves. Traditionally, and even up to the present time, many of the procedures performed by Otolaryngologists, involve repeated dilatation, laser ablation, advancement of mucosal flaps, free mucosal flaps and anterior and/or posterior cricoid split with insertion of a wedge of bone or cartilage in an attempt to enlarge the narrowed passageway. In general these have had only limited success. The development of techniques for primary resection and end-to-end anastomosis of the airway to the larynx with sparing of the recurrent laryngeal nerves has proven to be an excellent alternative. Shaw, in 1961, reported two patients with traumatic tracheal rupture treated by cricoid resection with anastomosis to the thyroid cartilage. In these patients the vocal cords were already paralyzed (43). Gerwat and Bryce at the Toronto General Hospital reported resection for laryngeal stenosis with partial cricoid resection and anastomosis of the trachea to the lower border of the thyroid cartilage anteriorly and to the cricoid lamina posteriorly, inferior to the cricoarytenoid joint (44). This was carried out only after carefully identifying the recurrent laryngeal nerves and tracing them up behind the cricothyroid joints before horizontally transecting the cricoid lamina posteriorly. The procedure incorporated a laryngeal release to reduce tension by mobilizing the laryngeal end of the anastomosis. A protective tracheostomy was placed and maintained for 2–3 weeks to reduce the danger of aspiration.

In 1975, Pearson and colleagues, also at the Toronto General Hospital, described a new method for resecting the airway at the cricoid level with preservation of the recurrent laryngeal nerves (45). This involved a line of transection which begins at the inferior border of the thyroid cartilage anteriorly and is carried obliquely down to transect the airway posteriorly through the upper end of the membranous trachea just at the inferior border of the cricoid lamina. The lamina is then reamed out using fine rongeurs, preserving the stout perichondrium on the backside of the lamina to avoid injury to the underlying laryngeal nerves. The perichondrium and the airway mucosa lying on the anterior surface of the cricoid lamina is also preserved but is transected at a more proximal level as necessary to get proximal to the damaged portion of the airway. By coring out the inferior portion of the thick cricoid lamina, the subglottic airway is thus enlarged allowing the trachea to be brought up for a primary anastomosis to a level up to 1 cm below the vocal cords. If necessary the membranous wall of the trachea is plicated to bring the tips of the upper tracheal ring together. This reduces the diameter and also forms a complete circle of cartilage for increased stability. The initial description of this procedure also incorporated laryngeal release to reduce anastomotic tension and a protective tracheostomy for 1–2 weeks postoperatively. This procedure was soon adopted by other centers as it provided an attractive solution to the problem of benign traumatic or post-intubation injury to the subglottic region. In most cases laryngeal release is found to be unnecessary and a protective tracheostomy is seldom required. Grillo and coworkers subsequently reported excellent experience with this procedure in 18 patients and in some cases modified the procedure by not coring-out the inferior portion of the cricoid lamina, but rather excising damaged airway mucosa on its anterior surface, and resurfacing this part of the airway with a broad-based flap of posterior membranous trachea wall shaped for that purpose (46). At the present time resection of the subglottic airway is most commonly employed for the treatment of idiopathic subglottic stenosis and for post-intubation injuries affecting the region of the cricoid cartilage and upper trachea. Such injuries may occur from placement of a tracheostomy site too high in the airway, either through or just inferior to the cricoid arch. This may occur inadvertently, but may also result from performance of an emergency tracheostomy in a life-threatening situation or from an elective tracheostomy in a patient with adverse anatomy such as kyphosis, obesity or other conditions limiting access to the trachea at the desired level.

Until the mid-1980s, airway anastomoses involving the trachea or main bronchi were almost exclusively related to repair and/or resection of a portion of the airway. Since then however, the most common need for end-to-end airway anastomosis relates to the airway connection made for lung transplantation usually at the level of the main bronchi. Such anastomoses are not under tension, do not pose significant technical challenges, and do not require fancy reconstruction techniques or mobilization of either proximal or distal ends of the anastomosis. Nonetheless, complications of this relatively straightforward airway anastomosis posed one of the major obstacles to successful lung transplantation making it the last of the vital organ transplants to be relatively successful.

The first attempt at human lung transplantation was by Dr. James Hardy in 1963 (47). This followed almost two decades of experimental work on lung or lobar transplantation conducted in many laboratories. Dr. Hardy's patient survived 18 days with death attributed to renal failure and malnutrition. Between 1963 and 1978 approximately 38 lung or lobar transplants were attempted around the world. Thirty-seven patients died in hospital and only one patient, following a prolonged postoperative stay, did leave hospital with limited benefit for the remaining months of his survival (48). Review of this world experience revealed that of the nine patients who survived more than 2 weeks following transplant, six died of dehiscence of the bronchial anastomosis and the remaining three had airway complications at the anastomotic site. Although many other issues related to lung transplantation remained to be resolved, complications at the bronchial anastomosis site became the cause of continued discouragement and the primary focus of ongoing research. There was widespread belief that rejection was playing a major role without any obvious remedy in sight. Immunosuppression following organ transplantation in that era consisted primarily of high doses of prednisone and azathioprine. It was recognized that interruption of the bronchial arterial supply by the transection of the donor bronchus left the donor end of the bronchial anastomosis ischemic. However it was clinically well established that sleeve resection of a lobe, which also involves an end-to-end bronchial anastomosis, was not associated with this type of consistent failure, nor was canine auto transplantation with complete excision of the lung followed by its reimplantation. In neither case was there the inevitable pattern of necrosis and anastomotic disruption observed following human lung transplantation.

At the University of Toronto, after more than a decade of laboratory investigation led by Dr. F.G. Pearson and colleagues, an initial attempt at clinical lung transplantation was made in 1978. This is involved a 19-year-old man who remained on chronic ventilatory support 6 months after an inhalation injury related to a house fire. Under the direction of Nelems, a right lung transplant was performed. The patient was weaned from ventilatory support during the first 2 postoperative weeks, but died on the 17th postoperative day of bronchial dehiscence (49). This outcome, coupled with the almost universal occurrence of bronchial anastomotic complications with patients who survived more than 2 weeks following lung transplantation, prompted a series of laboratory investigations into factors influencing bronchial anastomotic failure in a canine model of lung transplantation. Three potential factors were initially selected for evaluation, namely ischemia, the effects of immunosuppression and the potential influence of rejection.

To eliminate any factors associated with rejection, a series of canine lung auto-transplants were conducted with half of the animals receiving immunosuppression with prednisone and azathioprine and the other half receiving no immunosuppression. In the immunosuppressed animals, the same constellation of bronchial anastomotic complications including necrosis and disruption were seen. In animals receiving no immunosuppression, the bronchial anastomosis generally healed in primary fashion but with a significant incidence of moderate airway stenosis involving the distal side of the bronchial anastomosis. Further studies conducted on the effects of immunosuppression on bronchial anastomotic healing confirmed that it was the high-dose steroid that was primarily responsible and that azathioprine alone had no adverse effect on healing (50). Further studies showed that the then experimental immunosuppressive drug cyclosporine-A also had no adverse effect and could be substituted in the early post-transplant period for high-dose prednisone, resulting in much improved anastomotic healing (51).

The presence of bronchial anastomotic stenosis following canine auto transplantation in the absence of immunosuppression was thought to be the result of ischemia at the level of the distal bronchus due to transection of the bronchial artery supply during extraction of the lung. This leaves the reimplanted bronchus dependent on retrograde collateral bronchial artery circulation from intra-parenchymal connections between the pulmonary and bronchial circulations. The use of an omental pedicle wrap around the bronchial anastomosis at the time of reimplantation was found to restore systemic bronchial arterial circulation within a very short period of time and resulted in much improved anastomotic healing. In a series of canine lung auto transplantation, without the use of an omental wrap, the cross-sectional area of bronchial anastomosis was reduced by 53% whereas with the use of bronchial omentopexy the reduction in area averaged only 19% (52).

Subsequently a series of canine lung transplants was performed using an omental wrap around the bronchial anastomosis, and azathioprine and cyclosporine-A for initial immunosuppression with the introduction of prednisone in the second week. Six animals were euthanized between 100 and 135 days following transplant and all showed excellent healing of the airway anastomosis with little, if any narrowing (53).

In 1981 Reitz and co-workers at Stanford University initiated a heart-lung transplant program for patients with pulmonary vascular disease. Their success confirmed the ability of lung transplants to provide excellent pulmonary function to patients with end-stage lung disease and also demonstrated a much lower incidence of airway anastomotic complications then had previously been demonstrated with human lung transplantation (54). This improvement was attributed to preservation of the direct connections between the coronary circulation and the bronchial arterial circulation by way of the pericardial vessels which communicate with both systems. The use of cyclosporin-A for the heart-lung transplants may in retrospect also have played a role.

Encouraged by the success of the Stanford heart-lung program and by the laboratory success with canine lung transplantation, the University of Toronto embarked on a human-lung transplant program beginning in 1983. The long-term success of the initial two patients was subsequently reported (55). Over the ensuing years increasing experience with lung transplantation around the world, contributed to rapid improvements in the lung transplantation including donor and recipient selection, improved immunosuppression, improved methods of lung preservation and improved post-operative management. Early extubation following lung transplant is now commonplace. In retrospect it is apparent that the same issues that slowed progress with resection and reconstruction of the trachea and bronchi were also at play in the development of human lung transplantation, namely factors affecting wound healing at the anastomotic site. With tracheal and bronchial resection these factors included ischemia and tension from the anastomosis. With transplantation it was ischemia, adverse effects of immunosuppression and the prolonged postoperative ventilatory assistance required in the early days of lung transplantation. With lung transplantation, the omental wrap, which provided a "security blanket" around the anastomosis was no longer employed after several years. Improved lung preservation including both antigrade and retrograde pulmonary flushing at the time of donor extraction almost certainly improved the collateral blood flow from the pulmonary to bronchial vessels. This coupled with improved postoperative management and marked improvement in diagnosis and management of rejection has reduced the incidence of serious airway anastomotic complications following lung transplantation to 5% or less.

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Footnote

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