Review Article

Tracheal resection and reconstruction

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Purpose: To review the literature on tracheal and carinal resection and reconstruction, and to report the general approach to these patients, as well as the general guidelines for the safe administration of anesthesia. The airway management is extensively reviewed.

Source: Articles obtained from a Medline search (1960 to October 1997; keywords: tracheal surgery, carinal surgery, airway management). Textbook literature including the bibliographies were also consulted.

Principal Findings: Benign or malignant tracheal and carinal pathology causing obstruction can be managed in several ways but resection and reconstruction are the treatment of choice for most patients with tracheal stenosis or tumour. Surgery of the trachea is a special endeavour where the airway is shared by the surgeon and the anesthesiologist. The principal anesthetic consideration is ventilation and oxygenation in the face of an open airway. Ventilation can be managed in different ways, including manual oxygen jet ventilation, high frequency jet ventilation, distal tracheal intubation, spontaneous ventilation, and cardiopulmonary bypass.

Conclusion: The management of anesthesia for tracheal surgery presents many challenges to the anesthesiologist. Knowledge of the various techniques for airway management is crucial. Meticulous planning and communication between the anesthesia and surgical teams are mandatory for the safe and successful outcome of surgery for patients undergoing this procedure.

Objectif : Passer en revue la documentation concernant la résection trachéale et carénale ainsi que leur reconstruction, et indiquer la conduite à tenir dans ce cas avec les patients, aussi bien que les directives générales pour l'administration sécuritaire de l'anesthésie. La gestion des voies respiratoires a fait l'objet d'un examen poussé.

Sources : Des articles provenant d'une recherche dans Medline (1960 à octobre 1997; mots-clés: chirurgie de la trachée, chirurgie de la carène, gestion des voies respiratoires). Des monographies incluant les bibliographies ont aussi été consultées.

Constatations principales : La pathologie trachéale et carénale bénigne ou maligne causant de l'obstruction peut être traitée de différentes manières, mais la résection et la reconstruction sont le traitement de choix pour la plupart des patients atteints de sténose trachéale ou de tumeur. C'est une intervention spéciale où l'accès aux voies respiratoires est partagé par le chirurgien et l'anesthésiologiste. La considération anesthésique principale est la ventilation et l'oxygénation en présence de voies aériennes ouvertes. La ventilation jet manuelle avec de l'oxygène, la ventilation jet à haute fréquence, l'intubation trachéale distale, la ventilation spontanée et la circulation extracorporelle sont des variantes possibles de la ventilation dans ce cas.

Conclusion : La gestion de l'anesthésie lors d'intervention à la trachée représente de nombreux défis pour l'anesthésiologiste. La connaissance des diverses techniques de gestion des voies respiratoires est primordiale. Une planification méticuleuse et une bonne communication entre les équipes d'anesthésie et de chirurgie sont obligatoires pour assurer la sécurité des patients et le succès de ce genre d'intervention.

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TRACHEAL surgery was first performed in the 1950s. At the time, 2 cm were believed to be the maximum length that could be resected.[1] Progress in surgical and anesthesia techniques now permits more than half of the trachea to be safely excised in selected cases. The anesthesia literature does not contain large series but there are many case reports, many of which go back to the 1970s and 1980s. Conversely, large surgical series are found thanks to the work of thoracic surgeons such as Dr Hermes C. Grillo from Boston, Dr F. Griffith Pearson from Toronto, and Dr Louis Couraud from France. Together they total over 900 cases of tracheal and carinal surgery in the last 25 yr.

The aim of this article is to review and analyze ventilation methods and anesthetic techniques used in tracheal resection and reconstruction. A Medline search from 1960 to October 1997 was performed. Search terms included trachea, carina, resection, reconstruction, airway management and the following airway management methods: jet ventilation, high-frequency ventilation, tracheal ventilation, spontaneous ventilation, cardiopulmonary bypass. References quoted in pertinent chapters in thoracic surgery and anesthesia textbooks were also obtained. This search yielded 148 items, from the surgical and anesthesia literature. Of these, 122 were available to us. The reports dealing with diagnosis, non-surgical management and surgical techniques were summarized and included in this review only if they dealt with aspects having an incidence on the anesthetic plan. However, it was not within the scope of the present article to review this material critically. More attention was given to the various methods of ventilation, anesthetic drugs and monitoring techniques which have been described. There were no randomized, prospective studies. The vast majority of the pertinent literature consisted of case reports. Because of the limited number of such reports, all of them were reviewed and reported here. Consideration was given to the location and type of tracheal lesion, and to the choice of drugs and ventilation techniques which were available at the time the article was written.

Anatomy of the trachea (Figure 1)

The trachea extends from the lower border of the cricoid to the top of the carina spur. The anatomy has been extensively studied by Grillo [2] who reported an average tracheal length of 11.8 cm in the adult human with a range of 10 to 13 cm. There are approximately two cartilaginous rings per cm for a total of 18 to 22 rings. These C-shaped rings form the anterior and lateral walls of the trachea. The posterior wall is membranous. The internal diameter of the trachea measures about 2.3 cm laterally and about 1.8 cm anteroposteriorly. Looked at laterally, the trachea starts in a subcutaneous position at the cricoid level and ends in a prevertebral plane at the level of the carina. The proximal trachea is cervical and becomes mediastinal at the

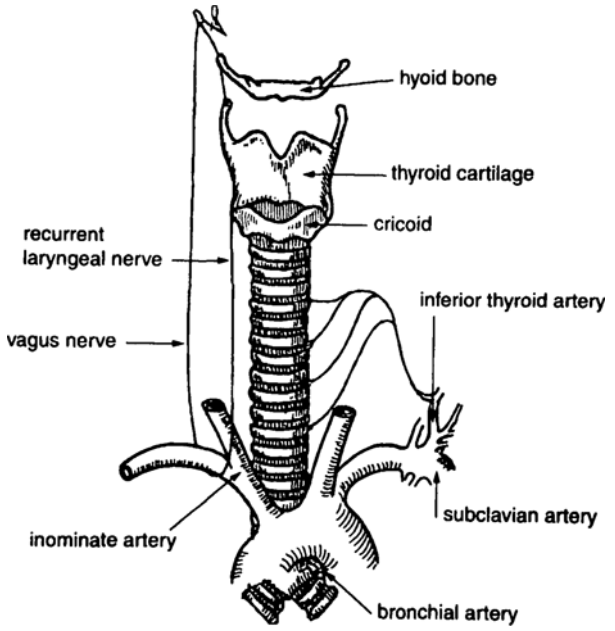

FIGURE 1 Tracheal anatomy

TABLE I Etiology of tracheal pathology

TUMOURS
Primary tumours
malignant
adenoid cystic carcinoma (cylindroma), squamous cell carcinoma, others
benign
neurofibroma, chondroma, chondroblastoma, hemangioma, pleomorphic adenoma
Secondary tumours
direct extension
thyroid, larynx, lung, esophagus
metastasis
lung, breast, lymphoma
INFLAMMATORY LESIONS
Post-intubation lesion
stricture, granuloma, malacia, tracheo-esophageal fistula
Post-traumatic stenosis
blunt trauma, penetrating injury, emergency tracheostomy
Post-infectious strictures
tuberculosis, diphtheria, histoplasmosis, rhinoscleroma
Burns
Connective tissue disease
systemic lupus erythematosis, Wegener's granulomatosis, amyloidosis
COMPRESSIVE LESIONS
Goitre
Vascular compression
thoracic aneurysm, congenital vascular rings, innominate artery aneurysm, anomalous right innominate artery, double aortic arch, complete tracheal rings and associated aberrant origin of left pulmonary origin
MISCELLANEOUS
sarcoidosis, relapsing polychondritis, osteoplastica tracheopathy, idiopathic

sternal notch. When the head is flexed, the trachea can become completely mediastinal. Conversely, head extension results in a longer portion of trachea becoming cervical. These observations are especially important when related to tracheal resection. The blood supply is segmental and approaches the trachea laterally. The upper trachea is perfused by the inferior thyroid artery, while the lower trachea is perfused by the bronchial arteries with contributions from the sub-clavian, internal mammary, innominate, internal thoracic and the supreme intercostal arteries.[1] The recurrent laryngeal nerves course posterolaterally to the trachea in the groove between the trachea and esophagus and enter the larynx between the cricoid and thyroid cartilages immediately anterior to the inferior cornua of the thyroid cartilage.

Etiology of tracheal pathology

Table I summarizes the different causes of tracheal obstruction.[3,4]

Post-intubation stenosis and tumours are the most frequent indications for tracheal resection and reconstruction. The incidence of post-intubation stenosis has decreased since the introduction of tracheal tubes with high-volume, low-pressure cuffs.[5] Factors associated with the appearance of these strictures are summarized in Table II. The site of stenosis is variable depending on whether the trachea was intubated orally/nasally as opposed to a patient who had a tracheostomy. Figure 2 depicts the different tracheal lesions resulting from tracheal intubation. Malignant primary tumours are relatively rare, the incidence estimated at 2.7 new cases per million per year.[6] The most frequent tumours encountered are squamous cell carcinoma and adenoid cystic carcinoma.

Clinical presentation

Symptoms may appear gradually or abruptly according to the underlying pathology. The symptoms are non-specific, often delaying diagnosis for many years.[3,4,6] Progressive exercise intolerance is a prominent symptom in over half of the patients. Other symptoms include hemoptysis, persistent cough that may or may not be productive, wheezing progressing to exercise stridor and to stridor at rest when the diameter of the trachea reaches 5 mm or less, dysphagia and hoarseness due to recur-

TABLE II Factors associated with the appearance of post-intubation stenosis or strictures

overinflation of the tracheal cuff
large-bore tracheal tubes
tube movement secondary to
spontaneous/assisted ventilation
heavy circuit tubing creating excessive traction on the endotracheal or tracheostomy tube
prolonged intubation
steroids
hypotension
diabetes
infection
nasogastric tube
survival of the patient (stenosis develops over time)

rent laryngeal nerve involvement. If the lesion is obstructing one or both of the mainstem bronchi, patients may have recurring bouts of unilateral or bilateral pneumonitis. Cyanosis is a very late and ominous sign, signaling almost complete occlusion of the airway.

All to often, the diagnosis of adult onset asthma is made and treated accordingly with bronchodilators and steroids. Patients not responding to this treatment are further evaluated at a later date, yet again delaying diagnosis. To this effect, Grillo states: *"Any patient who has received ventilatory support in the recent past or even not so recent past, who develops signs and symptoms of upper airway obstruction, has an organic lesion until proved otherwise."* [5]

Diagnostic studies

Patients with narrowed airway diameter are carefully observed while diagnostic evaluation is underway. Pulse oxymeter saturation is monitored and humidified oxygen (O_2) is provided as needed. The following diagnostic studies are used for identifying and/or characterizing a tracheal lesion.

Chest X-ray

The chest X-ray is generally not useful. It is often normal on initial examination.[7] Retrospectively, an abnormality of the tracheal lumen is sometimes seen.[3]

Linear tomography of the trachea

Linear tomography is probably the most accurate tool to characterize the lesion as to its degree, level, and length.[5,8]

Fluoroscopy

Fluoroscopy gives valuable information on the function of the glottis and larynx as well as identifying malacic segments.[5]

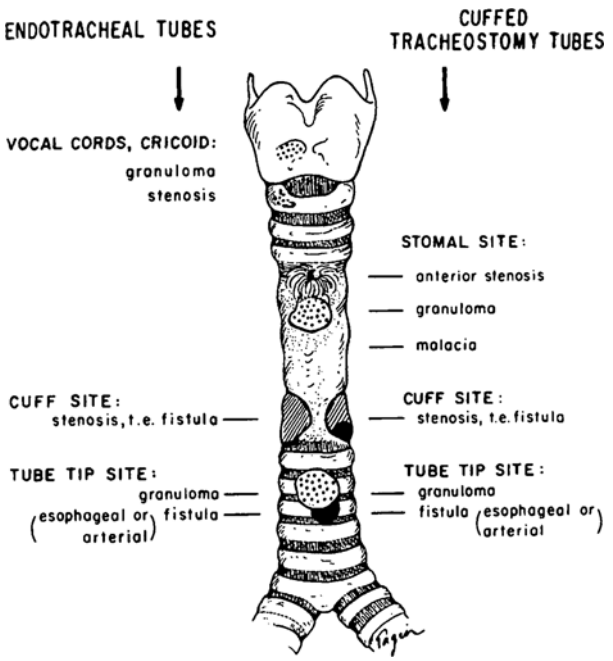

FIGURE 2 Type and location of tracheal lesions caused by intubation and tracheostomy. From: *Grillo HC.* Surgery of the trachea. Curr Probl Surg 1970; Jul: 3–59.

Computed tomography (CT)

Computed Tomography is a useful adjunct to evaluate extratracheal or extrabronchial involvement by tumour as well as esophageal and mediastinal invasion.[3] It is of little use for benign stenosis other than defining the exact location and gross extension of the obstruction.[4]

Barium study of the esophagus

For tumour investigation, barium study of the esophagus will identify esophageal involvement by invasion of tumoural process or extrinsic compression.[3]

Aortic arch angiograms

In selected cases of cancer, when cervical exenteration is planned (removal of larynx, portion of trachea and esophagus, and frequent mediastinal tracheostomy), aortic arch angiograms will identify tumour involvement of the four arteries supplying the brain.[9]

Pulmonary function tests

The interest in pulmonary function tests (PFTs) for high tracheal lesions lies in the flow-volume loop which identifies an obstruction and defines if it is intra- or extrathoracic, variable, or fixed (Figure 3). The degree

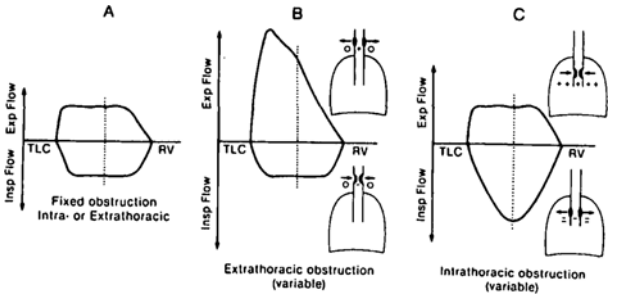

FIGURE 3 Maximal inspiratory and expiratory flow-volume loops depicting the effects of tracheal obstruction depending on its location (extrathoracic or intrathoracic) and its type (variable or fixed). (A) a fixed lesion, intrathoracic or extrathoracic, does not permit airway diameter changes at the site of obstruction during maximal inspiration and expiration. (B) a variable extrathoracic obstruction will affect forced inspiration as the negative pressure generated in the airway will be opposed at the lesion level when pressure becomes zero, thereby increasing the obstruction. During forced expiration, positive pressure in the airway will keep the trachea open at the site of the lesion, leaving the expiration curve unaffected. (C) A variable intrathoracic obstruction will show a normal maximal inspiratory curve as the negative intrathoracic pressure will keep the airway opened. The exact opposite effect occurs during forceful expiration when the intrathoracic pressure becomes positive and thus decreases airway diameter which will be most marked at the site of obstruction.
From: *Benumof JL.* Anesthesia for thoracic surgery, 2nd ed. Philadelphia: W.B. Saunders company, 1995: 536.

of stenosis can be estimated with a mouthpiece of varying and decreasing diameter. The flow-volume loop will change when the opening of the mouthpiece is smaller than the airway lumen. The forced expiratory volume in one second (FEV_1) in itself does not yield much information: the ratio of peak expiratory flow to FEV_1 is more helpful. If this ratio is ≥ 10:1, then airway obstruction should be suspected.[10]

For carinal lesions, complete assessment of pulmonary function is essential with the perspective of an eventual pneumonectomy. Reliable spirometry testing requires that at least one lung be normally ventilated.

Bronchoscopy

Bronchoscopic examination will be required in all patients with tracheal pathology.[4] This examination will define the nature of the lesion (from tissue biopsies), length, location and degree of obstruction. With a patient breathing spontaneously, segments of malacia will also be identified.

Flexible bronchoscopy may yield useful information but good judgment is in order before being done elective under topical anesthesia as it may provoke life-threatening acute airway obstruction due to bleeding, secretions, edema or from the bronchoscope itself.[3,6]

In cases of moderate to severe obstruction, endoscopic examination is usually deferred until the time of definitive treatment if surgery is to be done. If another modality of treatment is chosen, bronchoscopy should still be carried out in the operating room where both the surgical and anesthesia team are present and ready to intervene should loss of the airway occur. Rigid bronchoscopy is the gold-standard for characterizing the lesion and the tracheal wall surrounding it. Rigid bronchoscopy is preferable as it can core out tumours and provides a ventilation pathway. In case of bleeding, it may tamponade the source and allow easy insertion of epinephrine-soaked gauzes.[3] Suctioning is also more efficient.

Management of obstructive tracheal lesions

Patients presenting with airway obstruction can be managed in different ways. The goals of treatment are either cure or palliation. The different therapeutic options are briefly discussed below.

Irradiation

Squamous cell carcinoma and adenoid cystic carcinoma are both responsive to irradiation.[4] However, radiotherapy used alone is not a definitive treatment as recurrence of tumour occurs after a few years.[3,4] It is a good adjunct post-operatively. The advisability of preoperative radiation is questionable as the incidence of tracheal dehiscence is higher.[11]

Dilatation

Dilatation is the method of choice for emergency management of tracheal obstruction caused by stenosis.[8] It has very little value as definite treatment as recurrence will almost invariably occur.[5,8,12]

Dilatation is also used as a temporizing measure until surgery can be performed. It can be done repeatedly over time until full workup of the lesion is complete. It provides time for control of associated conditions such as infection or inflammation, or of an underlying medical condition.

After multiple dilatations, the risk of edema increases, therefore some recommend racemic epinephrine and steroids for a period of 24 hr (dose and route not specified) to prevent or minimize postdilatation edema.[3]

Laser

Laser therapy (CO_2 or YAG)[13] is used mostly as palliation for malignant lesions not amenable to resectional surgery. It cannot destroy the root of the tumour with-

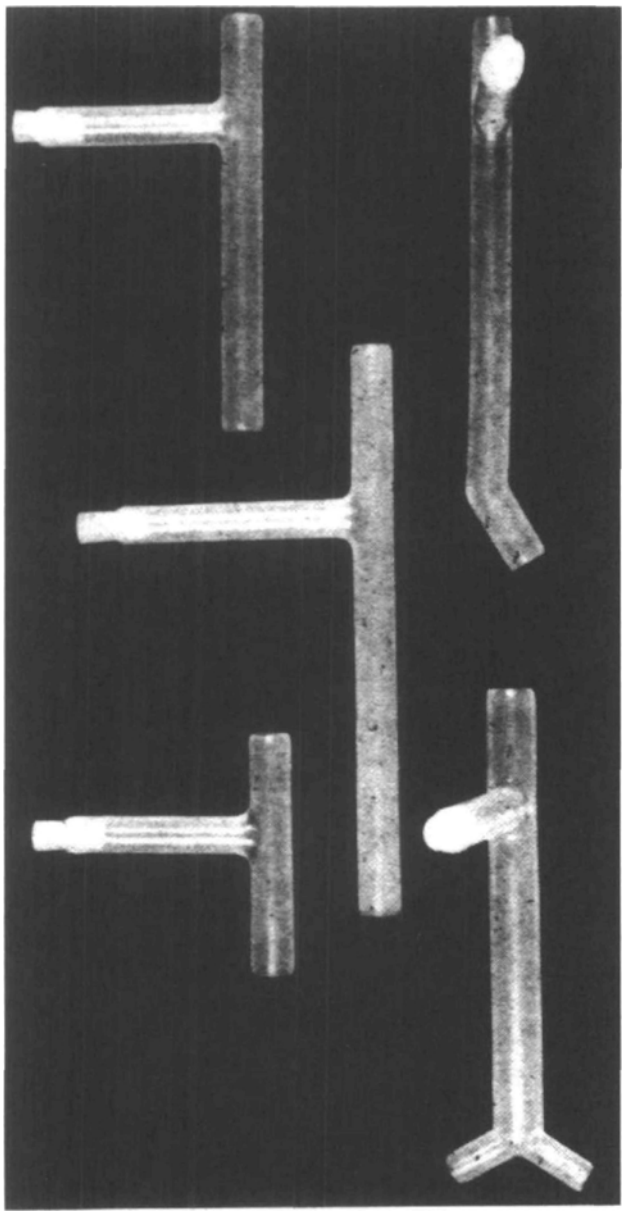

FIGURE 4 Examples of available silicone T-tubes and T-Y tubes. A T-tube consists of three limbs: an upper limb that may or may not protrude through the vocal cords, a distal limb that is placed in the trachea, and a side arm that will be placed percutaneously through an existing tracheostomy stoma or a new stoma. This side arm gives access to the airway in the same manner as a tracheostomy tube, and also insures that the stent stays in place. A T-Y tube differs from the T-tube in that the distal limb is Y-shaped to mold the carina so both arms may be inserted in each mainstem bronchi.
From: *Cooper JD, Pearson FG, Patterson GA, et al.* Use of silicone stents in the management of airway problems. Ann Thorac Surg 1989; 47: 371–8.

out destroying the tracheal wall so recurrence is inevitable.[3] It should not be tried as a definitive therapy for stenosis which are better treated by surgery as laser tends to destroy healthy adjacent trachea which is then lost for future reconstructive surgery if undertaken.[12,13]

Stents

Stents, in the form of T-tubes and T-Y tubes (see Figure 4 for details) may be used in many circumstances.[14,15] A stent can be used as ***palliation*** for patients with extensive tumours not amenable for surgery. It can be a definitive treatment for patients with benign strictures that are too extensive for surgery, for patients whose tracheas have been destroyed by multiple reconstruction attempts with associated failures, or for patients who are not candidates for surgery because of associated medical conditions. It can be inserted in the airway as a ***temporizing measure*** until the patient is ready for surgery. Finally, it can be used as ***adjunct to surgery***, providing stability to the newly anastomosed trachea.

Tracheostomy

If tracheostomy is deemed necessary to secure the airway, it must be placed in the most damaged area of the trachea to keep the healthy walls intact should tracheal reconstruction be performed at a later date.[3,8,16]

Surgery

Resection and reconstruction with primary anastomosis are considered the treatment of choice for managing most lesions of the trachea (see below).[3,5,6,8,17] In the case of malignant tumours, one must be certain that there is no extensive tracheal involvement, no deep invasion of the mediastinum, and no metastasis of the tumour. Adenoid cystic carcinoma is an exception because long survivals are noted in patients with metastasis in which cases surgery has proved beneficial.[3]

Reconstructive surgery

Patient selection

Patients must have a lesion known to be resectable, as defined by the diagnostic procedures above. The exact location of the lesion must be known, as well as its length.[18] The glottis must be functional, otherwise surgery will be in vain.[19] Patients with neuromuscular disorders or severe pulmonary pathology that will most likely require post-operative mechanical ventilation are not good candidates for tracheal resectional surgery as early extubation is highly desirable to prevent wound dehiscence as will be discussed later. To this effect, patients should also be weaned from ventilator before proceeding to surgery.[6,8,19]

Patients receiving steroid therapy will need to have them tapered off because steroids induce poor wound healing and are a cause of attenuated restenosis.[5] Steroids should be discontinued two to four weeks before surgery is undertaken.[20]

Timing of surgery

Tracheal resection should not be undertaken if active infection or inflammation at the site of surgery is present. These conditions will most likely lead to restenosis or, worse, wound dehiscence.[5] Again, ventilator and steroid weaning is done before surgery.

Tracheal mobilization and release procedures[18]

Tracheal mobilization and release procedures allow longer segment of trachea to be resected with primary (end-to-end) anastomosis to be performed with minimal tension on the fresh anastomosis to avoid dehiscence. With the exception of head flexion, all of these procedures are done by the surgeon.

Head flexion: this delivers the cervical trachea into the mediastinum.

Anterior pretracheal digital dissection: freeing the anterior trachea allows greater mobility of the trachea.

Suprathyroid laryngeal release: this procedure consists of cutting both thyrohyoid muscles transversely as well as the thyrohyoid membrane and ligament. It results in a laryngeal drop of 2 to 3 cm. Common postoperative problems with this technique are uncoordinated swallowing and aspiration.

Suprahyoid laryngeal release: the mylohyoid, geniohyoid and genioglossus muscles and the lesser cornua of the hyoid bone are transected and the body of the hyoid bone divided anteriorly so that the larynx drops 2 to 3 cm. Postoperative problems are less frequent using this release manoeuvre compared to the suprathyroid laryngeal release.

Intrapericardial right pulmonary hilar release: this will allow an elevation of the carina or distal trachea of 2 cm. The left hilum is seldom used because of its attachment to the aortic arc. Even when performed, a left hilar release does not yield as much additional length as the right hilum.

Dissection principles

Dissection is performed down to the pretracheal plane. At this point, dissection is carried out below the lesion and kept immediately on the tracheal wall, thus avoiding arterial trauma and lesions to the recurrent laryngeal nerves which course very close to the trachea. If the lesion is benign, no effort is made to identify the recurrent laryngeal nerves as this may increase the danger of injury to them.[2,5,8,18] Conversely, if the lesion is malignant, the nerves are identified to see if they are involved by the tumour process and one may have to be deliberately sacrificed. Great attention is paid to preserve the blood supply that arrives laterally to the trachea. Circumferential dissection is done only at the margins of the transection and kept to a minimum. Transection is then done below the lesion and dissection resumed until the diseased segment of trachea can be excised.

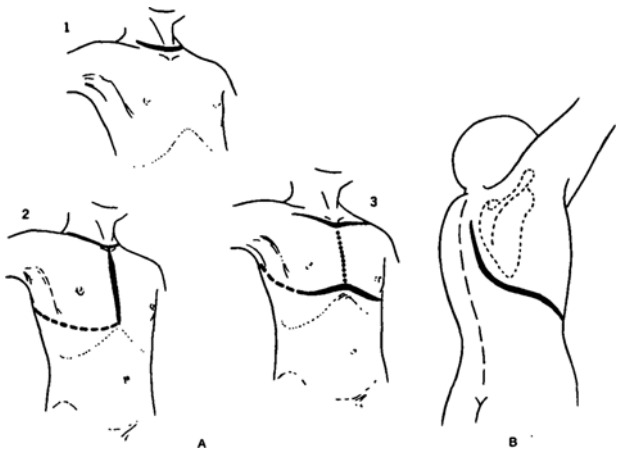

FIGURE 5 Surgical approaches to the trachea. High tracheal lesions can be accessed through a cervical incision (A1) that may need to be extended to a partial median sternotomy (A2). For complex lesions, a bilateral submammary thoracotomy may be done (A3). Low tracheal and carinal lesions are best approached through a right thoracotomy (B).
From: *Grillo HC.* Surgical approaches to the trachea. Surg Gynecol Obstet 1969; 129: 347–52.

Surgical approaches [2,18,21]

HIGH AND MID TRACHEAL LESIONS

Patients are positioned supine with an inflatable bag between the scapulas so that the neck is in full extension that is easily reversible with deflation of the air bag. Surgery proceeds through a generous collar incision with or without an upper sternotomy extension as depicted in Figures 5A1 and 5A2.

LOW TRACHEAL LESIONS

Patients may be positioned as above if head extension brings the diseased segment of trachea in the cervical region. If not, the patient is positioned in the left lateral decubitus position with the neck flexed. Surgery then proceeds through a right posterolateral thoracotomy in the fourth intercostal space, as shown in Figure 5B. Laryngeal release manoeuvres as well as

intrapericardial right pulmonary hilar release may also be done here to lessen traction on the anastomosis.

CARINAL LESIONS

A right posterolateral thoracotomy is the most frequent approach, again with the patient's neck flexed. The surgical field includes the neck, anterior chest and the right arm. Median sternotomy for limited carinal resection may be adequate. For extensive involvement of the carina, distal trachea and right mainstem bronchus, a bilateral submammary trans-sternal thoracotomy may be needed (Figure 5A3). Only rarely is left thoracotomy done because exposure of the carina is poor due to the aortic arc overlying the left hilum. Dissection follows the same guidelines as above. As already mentioned, a pneumonectomy may need to be performed because of extensive involvement of a mainstem bronchus.

Special considerations

Before performing end-to-end anastomosis, traction sutures are placed and tentative approximation done. For tracheal surgery approached by a cervical incision, the anesthesiologist will deflate the air bag between the patient's scapula and lift the head of the patient to about 30° which will result in cervical flexion. If excessive traction seems to be present, a laryngeal release manoeuvre will be performed. A guardian stitch is placed between the skin of the chin and the skin of the anterior chest to achieve head flexion of about 35° (Figure 6). This stitch which is left in place for 7 to 10 days, serves as a reminder to the patient not to extend the neck to avoid traction on the anastomosis. It is surprisingly well tolerated by patients.[22]

For carinal surgery approached by right thoracotomy, the neck is already flexed so no additional external manoeuvres are used. If excessive traction seems to be present on the anastomosis, intrapericardial right pulmonary hilar release will help in reducing the traction. Laryngeal release manoeuvres are of little help for carinal surgery. The amount of traction on the anastomosis relies on the experience of the surgeon.[22]

Early extubation is highly desirable as post-operative ventilation carries the risk of an endotracheal tube (ETT) cuff lying on a fresh anastomosis and positive airway pressure that can lead to wound necrosis or dehiscence.

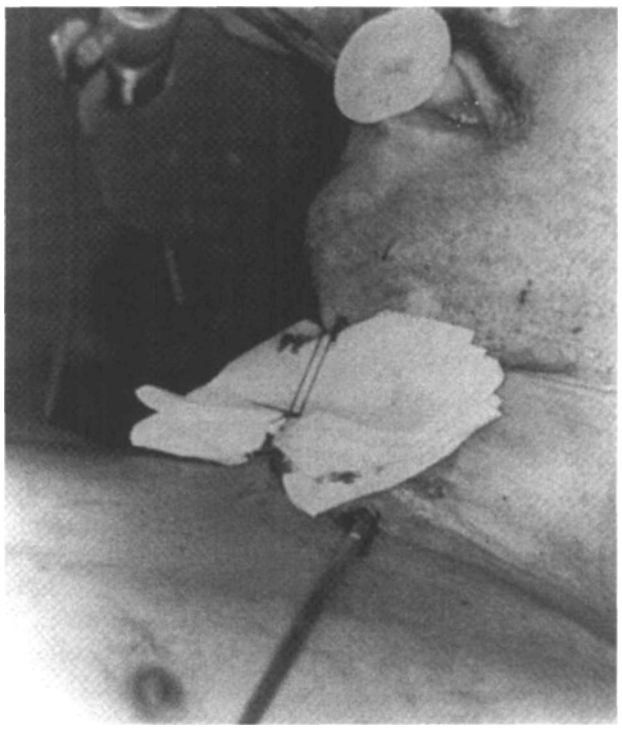

FIGURE 6 Depiction of the guardian skin stitch
From: *Heitmiller RF.* Tracheal release manoeuvres. Chest Surg Clin N Am 1996; 6: 675–82.

Anesthesia

General considerations

The airway is shared between surgeon and anesthesiologist. The surgeon must have maximal free access to the airway and an unobstructed surgical field with no interference by an ETT. Double-lumen tubes are not indicated because they carry the risk of trauma at the site of the lesion, and their bulk interferes with the surgical field. The anesthesiologist must provide adequate ventilation and oxygenation to a patient with a pre-operative critical airway, followed by an intra-operative transected airway, and finally a precarious post-operative airway that may be edematous due to multiple manipulations and also because of cervical flexion positioning.

Pre-operative sedation requires good judgment and will be dictated by the tightness of the obstruction. For patients with moderate obstruction, decreasing anxiety may be beneficial as quieter breathing results in a fall in airway resistance.[23] For patients with severely narrowed airway, respiratory depression must be avoided at all cost. Antisialogues should also be used with great caution as drying of secretions can cause a mucus plug that can obstruct an already tight lumen. It is best to defer all medication until the patient is in the supervised surroundings of the operating room.

PRE-OPERATIVE ASSESSMENT[10,23-25]

The anesthesiologist should know the underlying pathology of the lesion as well as being familiar with its anatomic characteristics and the severity of obstruction. All the diagnostic studies should be closely examined.

A detailed history should be obtained. Active smoking, difficulty in clearing secretions, exercise tolerance, the capability of tolerating the supine position are specifically looked for. A history of previous intubation (oral, nasal or tracheostomy) is recorded. Associated cardiopulmonary disease is identified and corrected if time allows. Physical examination should also be done with thorough evaluation of the airway. The trachea should be palpated, neck mobility in extreme position of flexion and extension is verified, the lungs and the trachea are auscultated, and the presence of stridor is sought, at rest and during maximal expiration with the mouth opened. Difficulties with mask ventilation and intubation must be anticipated well in advance. Routine blood work is all that is needed unless the patient presents with a medical condition requiring special investigation.

Cardiac screening in the form of echocardiography, thallium stress testing, and coronary angiography if indicated, should be done in all patients with suspected or known heart disease if time allows. In cases of carinal resection with possible pneumonectomy, cardiac investigation is strongly recommended.[26]

MONITORING AND EQUIPMENT

Monitoring should include ECG, saturation, capnography, esophageal stethoscope, blood pressure, temperature, a high inspiratory pressure alarm, and a nerve stimulator. An arterial line is placed in the left arm as compression, or rarely division, of the innominate artery will render inaccurate blood pressure readings if the line is placed in the right arm (Figure 1). Central venous pressure or pulmonary artery catheters are inserted only if the cardiopulmonary condition of the patient warrants their use. When tracheal resection is done as part of cervical exenteration , electroencephalographic (EEG) monitoring is used in the majority of patients. The EEG will monitor brain function should the innominate artery be clamped or divided during the procedure.[9]

Special required equipment must be readily available in the operating room before induction of anesthesia. (Table III) Additional equipment includes a liquid warmer, a warming blanket, a nasogastric tube, and a Foley catheter. As the patient's head is completely draped, eyes must be well lubricated and taped shut. Suturing the lids closed for the intra-operative period may be an option.

TABLE III Equipment required for tracheal reconstruction

1. Anesthesia machine capable of delivering up to 20 L·min^{-1} O_2
2. Assortment of endotracheal tubes
   a. Polyvinylchloride tubes, size 4 mm uncuffed to size 8 mm cuffed
   b. Unsterile flexible armoured tubes, 20-34 F
   c. Extra-long endotracheal tubes, 20-30 F
   d. Sterile armoured tubes, 20-34 F
3. Sterile corrugated tubing attached to a sterile Y-piece
4. High frequency positive-pressure ventilator (optional)
5. A second anesthesia machine

From: *Benumof JL.* Anesthesia for Thoracic Surgery, 2nd ed. Philadelphia: W.B. Saunders Company, 1995: 536.

INDUCTION

Induction of anesthesia in patients with severely compromised airways requires time and patience. The surgeon should be in the operating room during this time, and a set of rigid bronchoscopes must be ready for use in case of obstruction. Following five minutes of pre-oxygenation with O_2 100%, slow and gentle inhalational induction with the patient breathing spontaneously is the safest and the most recommended method.[23,27] High flow of O_2 should be used and ventilation can be assisted now and then, but spontaneous ventilation must be maintained. When an adequate depth of anesthesia is attained, topicalization of the airway with local anesthetics is done, and mask ventilation resumed. Muscle relaxants are avoided. Should they be given, the airway must first be secured and ventilation verified and shown to be possible. Awake intubation with the airway topicalized with local anesthetics and the patient breathing spontaneously is another option if bronchoscopy is not to be done first.[28]

Of the 28 case reports reviewed, nine proceeded with intravenous induction which included a depolarizing muscle relaxant,[29-34] a non-depolarizing agent,[35,36]or a muscle relaxant not identified[37] with no adverse events reported. Dodge[30] had a CPB on standby with both femoral artery and vein cannulated in case of complete obstruction during induction. The patient did not obstruct his airway. Patients may present with a tracheostomy or a T-tube in place. If decannulation of the trachea is certain to be tolerated, an armoured ETT can be inserted through the stoma in its place before induction.

The procedure usually starts with rigid bronchoscopy to define the lesion visually: exact location, extent, and amount of healthy trachea proximal and distal to the lesion. If the airway lumen is < 5 mm

because of stenosis, dilatation will be performed first. This is done serially with dilators and pediatric bronchoscopes.[38] Pearson uses esophageal bougies for dilatation which might be less traumatic.[39] The anesthesiologist should also take a look through the rigid bronchoscope to select an appropriately sized ETT and see how to direct it in the trachea.[6] A cuffed ETT 6 mm usually fits but an uncuffed ETT may have to be used if the airway lumen is still tight. The tip of the ETT is kept above the lesion or sometimes passed through it if the lesion is high enough that the ETT cannot be secured in the trachea if the tip is kept above the lesion. One must be careful when intubating through the stenosis. Tissue dislodgment, bleeding, and edema can occur. Also, the patent lumen can be lost because of the thickness of the ETT's plastic membrane that may encroach on the available stenotic cross-sectional area.[31]

MAINTENANCE

The use of several agents has been reported for maintenance. Most of the case reports date from the 1970s and 1980s and some of the agents mentioned are either no longer used today, or not used in Canada. Incremental doses or infusions of ketamine,[31] propanidid,[31] thiopentone,[40] meperidine,[41] althesin,[42–44] opioids with or without diazepam,[32,45,46]and, more recently, propofol,[28,34] have all been used during the tracheal resection and anastomosis phase. Maintenance with halothane,[29,30,33] and enflurane[35] has also been reported. No reports have been published using sevoflurane as the anesthetic agent for induction and maintenance. Nitrous oxide can be administered up to the point of transection and then replaced with O_2 100% during the stage of resection and reconstruction.

One should bear in mind that, ideally, the patient's trachea will be extubated at the end of surgery. Thus, short acting agents are preferable. Muscle relaxants that are easily reversible should also be used.

Ventilation methods

Ventilation must assured in face of an open airway. Gas exchange can be done in five ways.

MANUAL OXYGEN JET VENTILATION (LOW FREQUENCY JET VENTILATION)

Low frequency jet ventilation consists of manually triggering O_2 delivery under high pressure through a ventilation pathway (small catheter, ETT, bronchoscope...). This method usually delivers high tidal volumes (V_T).

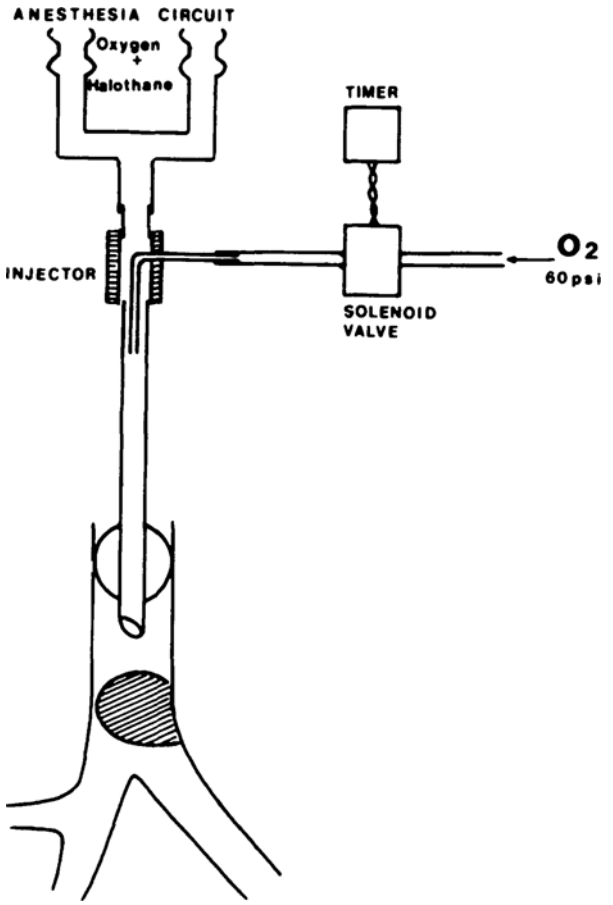

FIGURE 7 Diagram of system used for jet ventilation of an oxygen and halothane mixture. The injector is connected to the cuffed tracheal tube on one side and to the anesthesia circuit on the other side. The injector is driven by intermittent jets of oxygen (50 psi) that are automatically interrupted by an electronic timer controlling a solenoid valve.
From: *Baraka A, Mansour R, Jaoude CA, Muallem M, Hatem J, Jaraki K.* Entrainment of oxygen and halothane during jet ventilation in patients undergoing excision of tracheal and bronchial tumours. Anesth Analg 1986; 65: 191–4.

Case reports using manual oxygen jet ventilation go back to the 1970s.[40,41,47] For high tracheal lesions, intravenous or inhalational induction was carried out and the trachea was intubated orally with a small uncuffed ETT. The lungs were ventilated using intermittent positive pressure ventilation (IPPV) with a mixture of O_2 and nitrous oxide (N_2O) with or without a volatile agent. Upon opening the trachea, a long and narrow catheter was inserted through the ETT and passed into the distal trachea. The catheter was then attached to an oxygen source and ventilation

triggered manually, delivering O_2 100% at high pressures. The O_2 source was either the O_2 pipeline with an outlet pressure of 50 psi,[40] a mixing chamber attached to O_2 and N_2O cylinders to deliver O_2 and N_2O mixture during jet ventilation,[47] or the outlet of a bronchoscope injector.[41,42] The pressure could be adjusted in the range of 0 to 8 atm. Effective ventilation was assessed by lung or chest movement, auscultation, and regular blood gas analysis. The O_2 concentration reaching the lungs with this technique is not 100% as air is entrained into the distal trachea at the surgical opening (Venturi principle). The patient's lungs were ventilated in this manner until the anastomosis was completed, after which the catheter was withdrawn and IPPV resumed through the ETT which was either advanced beyond the anastomosis, or kept well above it. Maintenance of anesthesia was with intravenous drugs.

This technique has also been used for independent lung ventilation for carinal resection.[42] Two small catheters were inserted in the ETT and placed in each mainstem bronchus. Each catheter was connected to a different O_2 source so that the pressure used for ventilation of each lung could be adjusted according to the different compliance of each lung in the lateral position.

Jet ventilation has also be used as sole means of ventilation from induction until the end of surgery with a small ETT acting as the injector.[31,33] In one of these reports,[33] the ETT was attached to a Venturi injector that was connected to the gas outlet of the anesthesia machine. The gas mixture consisted of O_2 and halothane. The pop-off valve of the anesthesia circuit was kept wide open. With each jet insufflation, halothane was therefore entrained into the patient's lungs. (Figure 7)

The advantage of manual jet ventilation is good and free access to the surgical field, the surgeon being able to work around a small catheter. Drawbacks include possible hypercarbia due to hypoventilation, excessive movement of the catheter tip, blood and other debris entrainment into the distal trachea, spraying of blood across the surgical field caused by the high-flow O_2,[34] movement of the lungs and mediastinum, high V_T with possible hemodynamic repercussions, catheter plugging by blood or other debris, and contamination of the surgical field by the catheter which passes through the non-sterile proximal ETT. A patent passageway for gas outflow must be ascertained before using jet ventilation to avoid gas trapping with resulting barotrauma. If the degree of stenosis is severe and this method is used, slow respiratory rates should be used to permit long expiratory time. Also, the position of the catheter must be verified before injection of O_2, as a catheter tip inserted to far may produce barotrauma.

HIGH FREQUENCY VENTILATION

There are three modes of high frequency ventilation (HFV). High frequency positive-pressure ventilation (HFPPV) delivers V_T the size of anatomic dead space at a rate of 1-2 Hz (1 Hz = 60 breaths/min) using a ventilator with a negligible internal compliance so that the V_T generated is the V_T that is set. There is no air entrainment so the lungs receive only fresh gas. High frequency jet ventilation (HFJV) delivers pulses of small jet of gas derived from a high pressure source (about 50 psi) at a rate of 1.7-6.7 Hz. Air entrainment does occur so that the concentration of O_2 reaching the lungs is lower than what is set to be delivered. High frequency oscillation ventilation (HFOV) delivers V_T of 50-80 ml at a rate of 6.7-40 Hz.

HFPPV AND HFJV

High frequency positive-pressure ventilation was the first type of HFV used for major airway surgery in 1975.[48] Other reports followed with the use of HFPPV and HFJV for tracheal and carinal surgery.[16,17,36,44–46,49–51] The catheters used had an internal diameter ranging from 2 to 5 mm, with a length of either 45 or 50 cm. Of 32 patients reported, in 30 the trachea was intubated orally and the lungs ventilated with IPPV until the trachea was transected at which time HFV was initiated through the fine catheter inserted in the ETT and positioned either in the distal trachea or left mainstem bronchus. In one patient the trachea was intubated orally and the HFV was used from start to finish by way of a fine catheter inserted in the ETT.[48] In the other patient intubation was with a fine catheter (no ETT) and the lungs were exclusively ventilated with HFV.[36]

There is no optimal HFJV setting. It should be adjusted on a case-by-case basis. Breathing rate ranged from 1 to 14 Hz, driving gas pressure varied from 5 to 60 psi, and insufflation time set between 20 and 40%. In all the cases reported, blood gas analysis demonstrated adequate gas exchange, and vital signs were stable. Surgical conditions were excellent.

The use of two HFJV systems for ventilation of both lungs independently is possible when surgery involves the carina.[34,37] Two catheters are inserted in the ETT and placed in each mainstem bronchus. This particular method permits driving gas pressure adjustments for each lung (different compliance).

HFOV

High frequency oscillation ventilation was investigated for thoracic procedures.[52] These consisted of parenchymal lung resection only (lobectomy, pneumonectomy and wedge resection). The authors con-

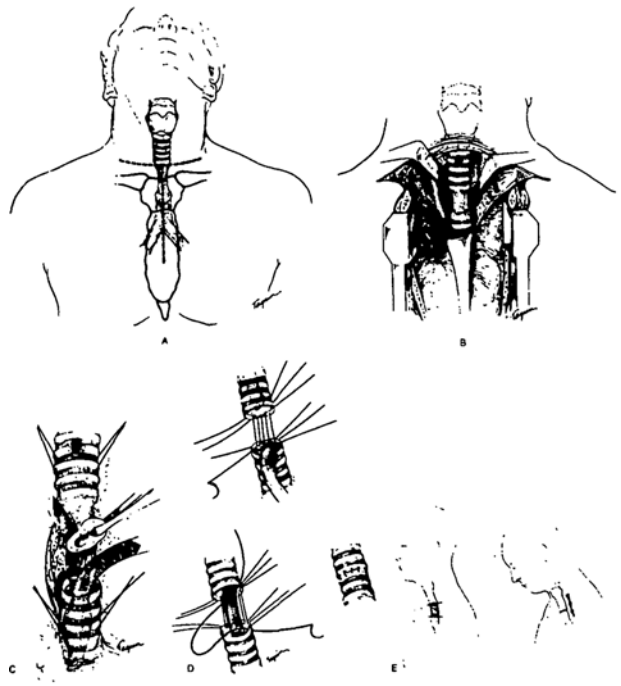

FIGURE 8 Upper trachea surgery through a cervical incision with partial median sternotomy. Airway management is done with an endotracheal tube (ETT) passed into the distal trachea during resection of the diseased trachea. In this example, the proximal ETT is passed back into the distal trachea once that all of the sutures are placed on the posterior membrane. Notice the effect on head flexion on the anastomosis which greatly reduces traction. From: *Grillo HC.* Surgery of the trachea. Curr Probl Surg 1970; Jul: 3–59.

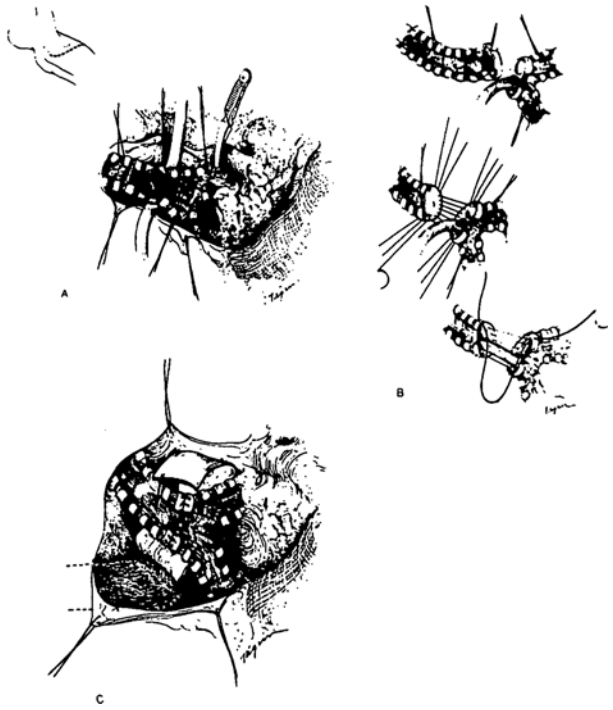

FIGURE 9 Low trachea surgery. The trachea is approached through a right thoracotomy. Airway management (B) is done through the operative field with a sterile ETT placed in the left mainstem bronchus while surgery proceeds up to the sutures on the posterior membrane. The proximal ETT is then passed into the left main stem bronchus until the rest of the sutures are placed. Notice the clamp on the right pulmonary artery (A). From: *Grillo HC.* Surgery of the trachea. Curr Probl Surg 1970; Jul: 3–59.

cluded that HFOV was not suitable for major airway surgery because of changes in airway diameter and of a mediastinal bounce with each insufflation. Investigations with this method during tracheal surgery where the trachea is open will need to be performed to confirm the above conclusion.

Advantages of HFV include improved gas mixing and accelerated diffusion which results in good gas exchange, the presence of auto-PEEP (positive end-expiratory pressure) due to continuous positive airway pressure which increases functional residual capacity and decreases ventilation-perfusion mismatch and also decreases the risk of atelectasis,[34] minimal hemodynamic repercussion, unobstructed surgical field, minimal lung expansion and mediastinum movement providing the surgeon with a quiet field, decreased danger of aspiration of blood and other debris into the distal airway due to continuous outflow of gases,[49] and less catheter displacement. Here also, free egress of gas from the lungs must be ascertained to avoid barotrauma.

DISTAL TRACHEAL INTUBATION AND INTERMITTENT POSITIVE PRESSURE VENTILATION

High and mid tracheal surgery

This technique of lung ventilation is, by far, the most frequently used. In its simplest form, the trachea is intubated above the lesion. Once the trachea is opened, the ETT is simply pushed across the gap and positioned by the surgeon in the distal trachea.[29,53] Drawbacks to this technique are trachea rupture, tissue dislodgment, bleeding, obstructed surgical field, and contamination of the surgical field by the non-sterile ETT. A more "logical" technique was described back in 1969 by Geffin *et al.*[23] and is still widely used.[3,5,28,30,35,54–58] It is also our method of choice for airway management. Following tracheal intubation with the ETT above or sometimes through the lesion, the lungs are ventilated using IPPV. Once the trachea is transected by the surgeon, the proximal ETT is pulled back, but kept in the trachea, and a new and sterile ETT is inserted by the surgeon, through the surgical field, into the distal tra-

chea if the tracheal lesion is high (Figure 8), or in the left mainstem bronchus if the lesion is near the carina or at the carina itself (Figure 9). Sterile tubings are then attached to this distal ETT and passed to the anesthesiologist so that IPPV can be resumed. Once the segment of diseased trachea is excised, end-to-end anastomosis is carried out. For this stage of operation, short intermittent apneic periods are permitted during which the distal ETT is removed from the trachea for suturing. There is no defined "optimal" apneic time. Patients should be receiving O_2 100% to ensure an oxygen rich FRC, and vital signs should be observed closely. We usually allow a maximum of three minutes even if the saturation still reads above 98%. If the saturation level decreases before that, ventilation is resumed sooner. Between apneic periods, the lungs are manually hyperventilated with O_2 100% until the $P_{ET}CO_2$ decreases between a normal range of 30 to 35 mmHg. During this "hyperventilation-apnea" period, the surgeon starts by putting sutures on each end of the trachea without tying them, and then reapproximates the ends and ties the sutures on the posterior membrane. The neck is flexed during this part of surgery. Once all the sutures are in place and the posterior membrane is securely anastomosed, the distal ETT is removed, and the proximal ETT is advanced beyond the anastomosis, either in the distal trachea or the mainstem bronchus. The surgeon then ties the remaining sutures.

There are ways to secure the proximal ETT for readvancement in case of accidental extubation (the head is inaccessible to the anesthesiologist in most cases). Before pulling back the proximal ETT, a suture or surgical tape passed through the Murphy's eye can be secured on the surgical drapes, or a sterile flexible and long stylet can be passed retrogradely through the ETT and secured on one end by anesthesiologist and on the other end by the surgeon.

Low tracheal and carinal surgery

For precarinal lesions where the stump is very short, a standard ETT may pass endobronchially as the total length of the cuff plus the plastic segment distal to the cuff may be longer than the stump. The surgery can be carried out under one lung ventilation (OLV) if tolerated by the patient. If not, the pulmonary artery can be temporarily clamped on the non-ventilated side, thus reducing shunting. An alternative is to intubate both mainstem bronchi with separate ETTs and to apply CPAP (continuous positive airway pressure) to the non-dependent lung, or to ventilate both lungs with two anesthesia machines or to connect both ETTs to a Y piece and ventilate both lungs with the same anesthesia machine.[59] Another method would be to use manual jet ventilation or HFV to the non-ventilated lung.[60] One group used a Foley catheter whose tip was cut off exactly beyond the lower border of the balloon.[32] It provided a satisfactory seal and ventilation of both lungs was achieved, whereas a standard ETT had to be endobronchial to avoid cuff herniation and obstruction of the surgical field. Another group tried cutting the segment distal to the ETT cuff.[61] The result was a loss of seal because the pilot tube extends beyond the cuff. Insertion of a surgical needle tip of appropriate size to block the open distal end managed to allow an adequate seal. The same group used a Shiley tracheostomy tube for bilateral lung ventilation in another patient. A problem arose when the proximal ETT tube was readvanced past the fresh anastomosis: the proximal edge of the cuff had to lie 4 mm below the anastomosis to allow bilateral ventilation, requiring frequent fibreoptic examination to ensure that the cuff did not move to lie on the anastomosis. An alternative would have been to position the cuff above the anastomosis and ventilate the patient with small V_T at a higher respiratory rate to keep peak pressures low. The same authors comment on the possibility of requesting a particular tube design from ETT manufacturers, emphasizing the need for communication and planning between anesthesiologist and surgeon.

SPONTANEOUS VENTILATION

Only two case reports were found where the patients breathed spontaneously throughout the procedure. In one of these reports,[43] anesthesia was induced in two patients with halothane and the trachea was intubated with the tip of the ETT proximal to the a tracheal stenosis that was to be resected. Once the trachea was opened, a flow of 8 $L \cdot min^{-1}$ O_2 was allowed to flow through the ETT and immerse the surgical field, the patients breathing on their own. Anesthesia was maintained with a continuous intravenous althesin infusion. In the other report,[62] a patient presented for tracheoesophageal fistula repair, without tracheal resection, through an existing and patent tracheal stoma. Anesthesia was induced with a bolus of propofol and maintained with a continuous intravenous propofol infusion. Oxygen was delivered at an initial flow of 5 $L \cdot min^{-1}$ through a 12 F catheter passed through the stoma and positioned above the carina. Spontaneous ventilation was maintained. All three patients did well during surgery and also postoperatively. The tracheas were easily and rapidly extubated. In addition to hypercarbia and respiratory acidosis, other disadvantages to this technique are aspiration of blood and debris despite careful suctioning by the surgeon, and cough. In the second report, cough did occur, but responded well to small boluses of propofol.

CARDIOPULMONARY BYPASS

Cardiopulmonary bypass (CPB) was very popular in the 1960s for carinal surgery.[63–65] At first glance, CPB seems like an easy way to insure gas exchange in a situation where the major airway is opened, but it is fraught with risk. Systemic anticoagulation augments the chances of bleeding, especially if the dissection is extensive and complicated and lung manipulation unavoidable. The duration of surgery is increased, and the CPB carries risks itself. One death was clearly attributable to this technique.[66] The patient developed a pulmonary intraparenchymal hemorrhage leading to fatal hypoxemia when he was weaned from bypass.

Cardiopulmonary bypass has been used as a first line airway management in at least two occasions for nearly complete airway occlusion.[67,68] Standby CPB for induction of anesthesia in patients with severely obstructing lesion is a reasonable approach. The use of CPB in pediatric patient is also reasonable considering the smaller airway, leaving us with fewer manoeuvres before total obstruction.[69]

Post-operative airway management

A small ETT or tracheostomy tube, or a T-tube with upper limb 0.5 to 1 cm above the vocal cords can be inserted at the end of surgery in cases where glottic edema is a concern, or for patients requiring ventilatory support. The ETT or tracheostomy tube should preferably be uncuffed. If a tracheostomy is performed, it will be done distal to the anastomosis. If an ETT or tracheostomy tube is used, humidified O_2 should be provided. The ETT is removed as early as possible. T-tube with the cervical arm closed to permit normal breathing passageway is preferable because it preserves humidification of the airway, it is less irritating to the tracheal mucosa, and it serves as a stent for the anastomosis. It is also well tolerated by patients.

If a patient requires reintubation, it is best done using a flexible fibreoptic bronchoscope (FOB) with the ETT slided over the FOB into place into the trachea. As mentioned before, the post-operative airway is considered difficult. Also, the position of the tip of the ETT can be verified in respect to the anastomosis.

Clearance of secretions is essential, with the help of chest physiotherapy and sometimes with the FOB. The patient is kept in a headup position to diminish swelling. Racemic epinephrine, diuretic, restricted fluid intake, and steroids are used as needed (dose and route not specified).

TABLE IV Complications of tracheal resection and pathology

Complications related to the surgical site
Granulation tissue
Stenosis (partial or complete)
Dehiscence
Failure of wound healing
Recurrent laryngeal nerve dysfunction
Wound infection
Persistent stoma
Hemorrhage
Malacia
Simple air leak with subcutaneous emphysema
Laryngeal edema
Aspiration
Deglutition problems
Tracheoesophageal fistula
Tracheoinnominate fistula
Esophagocutaneous fistula
Non tracheal surgery related
Respiratory failure
Pneumonia
Pulmonary embolism
Pneumothorax
Myocardial infarction
Deep vein thrombosis
Atrial fibrillation
Tetraplegia
Guillain-Barré syndrome[74]

Complications

Complications of tracheal surgery depend on the underlying pathology and on the degree of dissection and mobilization of the trachea (Table IV).

The incidence of *granulation* tissue has decreased since surgeons started using absorbable suture material. *Dehiscence* of the anastomosis usually results from excessive traction or from necrosis due to destroyed blood supply (excessive circumferential dissection). Mortality is high. The risk of dehiscence can be diminished by placing a vascularized flap over the anastomosis at the time of surgery. *Infection* is rarely a problem despite a contaminated wound. One study reports an infection rate lower than 2%.[70]

Three cases of post-operative *tetraplegia* have been reported.[71–73] Hyperflexion of the neck was implicated as cutting the chin stitch resulted in recuperation in two cases. The other case of tetraplegia was irreversible. The effect of the relative hypotension caused by the sitting position post-op may have contributed to spinal cord ischemia.

Conclusion

Tracheal resection and reconstruction constitute major and complex surgery performed in specialized centres. Despite the relatively low occurrence of patients suffering from tracheal pathology requiring aggressive treatment, major advances in surgical and anesthesia techniques have been achieved over the years, making this procedure safe and worthwhile for

selected patients with a tracheal or carinal lesion. Team work consisting of communication, coordination, and cooperation between surgeon and anesthesiologist is mandatory. Meticulous planning and anticipation of problems cannot be emphasized enough.

Numerous anesthesia techniques for airway management have been reported. The knowledge of these must be well known to the anesthesiologist involved in the care of a patient undergoing tracheal or carinal surgery.

Many articles still report the use of enflurane for induction of anesthesia as well as maintenance using the distal tracheal intubation mode of ventilation. It will be interesting to see the place of sevoflurane and desflurane in future reports. There has been no focus on the use of narcotics and the possibility of remifentanil titration has not been addressed.

Acknowledgments

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