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Tracheal damage

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Abstract. *Tracheal damage*. Blunt/penetrating trauma and inhalation injuries to the trachea can result in acute airway compromise, with life-threatening implications. Early assessment, identification, and prompt and appropriate management are of paramount importance in order to reduce patient morbidity and mortality. Signs and symptoms of these injuries are specific and sometimes subtle, and their seriousness may be obscured by other injuries. Diagnosis can therefore be challenging, requiring a high index of suspicion. Indeed, diagnosis and treatment are often delayed, resulting in attempted surgical repair months or even years after injury.

Laryngoscopy, flexible and/or rigid bronchoscopy and computed tomography of the chest are the procedures of choice for a definitive diagnosis. Airway control and appropriate ventilation represent the key aspects of emergency management. Definitive treatment depends on the site and the extent of injury. Surgery, involving primary repair with direct suture or resection and end-to-end anastomosis, is the treatment of choice for patients suffering from tracheal injuries. A conservative approach must be considered for the paediatric population and selected patients with mainly iatrogenic damage.

We present a review of the incidence, mechanisms of injury, clinical presentations, diagnosis, initial airway management, anaesthetic considerations and definitive treatment in the case of tracheal damage from blunt/penetrating trauma and inhalation injuries.

1. Introduction

Acute post-traumatic tracheal damage is rare, but represents a potentially life-threatening spectrum of injuries.[1] Tracheal injuries can cause airway obstruction, with resulting respiratory insufficiency. Many patients die at the trauma scene from acute respiratory insufficiency or within two hours from associated injuries.[2]

Airway damage may be the result of traumatic or inhalation injuries. The main traumatic causes include blunt or penetrating injuries to the neck and/or chest, and iatrogenic lesions of the tracheobronchial tree following tracheal intubation and percutaneous tracheotomy.[3-5]

Tracheal injuries may involve the larynx (laryngotracheal trauma, or LTT) and/or the bronchi (tracheobronchial trauma, or TBT). Due to the degree of blunt trauma required to produce airway damage, associated injuries are also common in this group of patients and may be the primary determinant of patient outcome. Airway injuries are the first priority in trauma; due to their acuteness and critical importance in stabilizing the patient, initial management steps may proceed simultaneously with a diagnosis of airway pathology and associated injuries.[6]

In an acute setting, clinical diagnosis is delayed in up to 50% of cases due to low suspicion levels of the examiner, ambiguous clinical symptoms and poor knowledge of injury mechanisms.[7] Regardless of mechanisms or anatomic sites of injury, a delay in diagnosis is the single most important factor influencing patient outcome.[8] Early identification of tracheobronchial injury (TBI), meticulous airway management and appropriate treatment are therefore essential in the case of such potentially lethal damage.[9,10]

Treatment of these patients is challenging, however. The physician must first secure a patent

airway allowing adequate ventilation, and then ensure repair of the airway injury, as well as treating associated damage, with minimal impact on respiratory function and the patient's quality of life.[11]

2. Incidence

Blunt injury to the airway is uncommon thanks to anatomic protection by the mandible and sternum anteriorly, the spinal column posteriorly, and the mobility and elasticity of the upper airway itself.[12] Indeed, the larynx and cervical trachea are injured in less than 1% of patients admitted to hospital for blunt trauma. Schaefer[13] reported an LTT incidence of one in 30,000 emergency visits over a 27-year period for blunt injuries occurring alone.[14]

Little information is available on the incidence of tracheal or bronchial injury as a result of blunt trauma. One reason for this may be that 80% of patients with blunt traumatic injury to the trachea and/or bronchus die before arriving at hospital and therefore remain unreported.[15,16] In a review of 1,178 trauma autopsy reports, only 2.8% of tracheobronchial rupture cases were identified, and 81% of these patients died before reaching hospital.[17]

Penetrating airway injuries to the neck are also relatively uncommon. Capan *et al*.[18] reviewed 17 reports published between 1965 and 1989 describing acute cervical airway damage. Only around 300 patients were identified, giving an average of <3 cases per year per reporting centre. About one-third of airway injuries involved the larynx and two thirds the cervical trachea.[19]

In 1987, Bent *et al*.[20] reported an incidence of 1 in 5,000 emergency visits for both blunt and penetrating LTT. Prompt diagnosis and treatment are essential to limit morbidity, mortality and long-term complications.[2,3,21]

Inhalation injury complicates burns in approximately 10%–20% of patients and significantly increases morbidity and mortality rates.[22-24]

3. Mechanisms and sites of injury

The majority of laryngeal and/or tracheal injuries are caused by blunt trauma. Other aetiologies include penetrating trauma, aspiration of foreign bodies, iatrogenic damage and inhalation of noxious or hot gases.[12]

TBIs are encountered with increasing frequency as a result of improvements in pre-hospital care and early initiation of the advanced trauma life support protocol.[8] In 1971, Ecker *et al*.[15] reported that of 27 patients encountered over a 10-year period, only nine were alive upon reaching the emergency room. In their post-mortem review of 1,178 subjects who died of trauma, Bertelsen and Howitz found that only 33 had TBIs and that 27 of these died almost immediately.

Trauma to the distal tracheobronchial tree most often results from rapid horizontal deceleration causing an airway injury, typically within 2 cm proximal or distal to the carina.[7,25] In their review of 265 blunt TBIs, Kiser *et al*.[16] identified motor vehicle accidents as the most frequent mechanism of injury (59%), followed by crush injuries (25%). The same review showed the right bronchus to be most often the site of injury (47%), and 76% of injuries to be within 2 cm of the carina. Mortality is generally higher with tracheal injuries (26%) than bronchial injuries (16% right, 8% left).

3.1. Blunt injuries

Blunt injuries to the airways are frequently the result of direct blows, severe flexion/extension damage, or crush injuries to the neck or chest.[12] This type of injury is often the result of a motor vehicle crash or strangulation.

Blunt injury to the cervical trachea is usually caused by a direct blow to the anterior trachea ("clothesline injury"). Neck hyperextension can result in tracheal tears, paramedian vertical fractures of the larynx and trachea, and/or even complete laryngotracheal separation. Direct blows to the neck usually injure the thyroid and cricoid cartilages.[11] A specific type of injury combining both mechanisms is the one produced when neck hyperextension from sudden deceleration during a vehicle accident is followed by the direct collision of the neck with the steering wheel or the dashboard ("padded dashboard syndrome").[11,26] The cervical trachea can also be injured when violently compressed, along with the oesophagus, against the cervical spine.[27] Finally, the trachea can be traumatized by the seat belt in a head-on collision, and sometimes by the sudden increase of intratracheal pressure against a closed glottis.[28]

Tracheobronchial blunt injuries can also be explained by various hypotheses. The first suggests that when the glottis is closed, excessive pressure

in the tracheobronchial tree causes airway blowout at the point of weakest resistance. Rupture can occur in these circumstances when the intraluminal pressure exceeds the elasticity of the membranous trachea and bronchi, and occurs most commonly at the junction of the membranous and cartilaginous airways.

The second hypothesis suggests a combination of an anterior-posterior decrease in chest diameter and a lateral increase in diameter, causing the lungs to be pulled out laterally. Disruption of the main bronchi and/or the carina occurs if this lateral force exceeds tracheobronchial elasticity.

The third hypothesis suggests that severe and sudden deceleration can give rise to shear forces that may disrupt the airway at points of relative fixation such as the cricoid cartilage and the carina, similar to the mechanism of traumatic injuries to the thoracic aorta.[29]

3.2. Penetrating injuries

Although penetrating injuries can involve any part of the airway, the cervical trachea is the structure most commonly injured.[12] The larynx is injured in approximately one third of upper airway injuries, with the cervical trachea accounting for the remaining two thirds.[19] Death in patients with penetrating airway trauma is usually due to an associated vascular injury and is rarely due to the airway injury itself.[25]

3.3. Intubation injuries

Injuries resulting from endotracheal intubation have been one of the most common surgical indications for tracheal resection and reconstruction. In a study by Grillo,[30] of 208 patients who received operations to repair injuries resulting from tracheal intubation, 185 had tracheostomy injuries and 23 had injuries from endotracheal intubation. Among these 23 patients, 22 suffered from cuff injuries. Cuff injuries also accounted for approximately half of the injuries in the patients who had tracheostomies. The percentage of laryngeal injuries due to intubation is unclear, but a prospective study by Kambic and Radsel reported it to be approximately 0.1%.[31]

High pressures within endotracheal tube cuffs, commonly used prior to the introduction of low-pressure cuffs, are thought to be the aetiology of most injuries following endotracheal intubation. Since the development of high-volume, low-pressure cuffs, the incidence of tracheal stenosis from this type of injury appears to have decreased, although these injuries continue to occur and to be the most common indication for tracheal resection and reconstruction.[32] Other injuries include tracheal erosion, tracheoesophageal fistula, trachea-innominate artery fistula, and bronchial rupture.

3.4. Inhalation injuries

The inhalation of extremely hot steam, gas, or other noxious fumes will tend to injure the larynx and cervical trachea, and occasionally damage the lower airway. Early intubation or tracheostomy is essential in most cases, due to the rapid development of upper airway oedema.[12]

Thermal airway injury is generally limited to supraglottic structures, whereas the lower airway is more often chemically injured. Steam inhalation, however, causes damage to both upper airways and direct thermal injury to the lungs.[24,33] This thermal damage to the upper airway may be caused by either steam inhalation and explosions.

Smoke inhalation is an important cause of fire-related morbidity and mortality, accounting for several thousands of deaths annually in the world. It also increases post-acute mortality in about 30% of cases. Most smoke toxicity can be explained by toxic gases exerting their effects through asphyxiation, systemic toxicity, or direct effects on respiratory tissue.[24]

Many products of combustion, such as carbon dioxide (CO_2) and carbon monoxide (CO), function as simple asphyxiants. This effect may be further exacerbated by the hypoxic fire environment. CO functions systemically as an asphyxiant by competitively displacing oxygen from haemoglobin and binding to cytochrome oxidase at the mitochondrial level.[24] In contrast, hydrogen cyanide binds only to cytochrome oxidase.[34]

Other combustion products such as halogen acids, formaldehyde and unsaturated aldehydes act as respiratory irritants.[24] The chemical irritation causes denuding of the respiratory mucosa, inducing the host inflammatory response.[24] Moreover, the chemical injury stimulates vasomotor and sensory nerve endings to produce neuropeptides. These neuropeptides then induce bronchoconstriction and nitric oxide synthase (NOS) to generate reactive oxygen species (ROS).[24,35]

The loss of an intact bronchial epithelium and the effects of ROS result in a loss of plasma

proteins and fluid from the intravascular space into the alveoli and bronchioles.[36]

The primary mechanism of hypoxaemia following a smoke inhalation injury involves increased blood flow to the injured lung segments and decreased ventilation of collapsed segments, contributing to a ventilation-perfusion mismatch.[24] Atelectasis, dysfunction of the immune system and mechanical ventilation are predisposing factors for pneumonia, a common inhalation injury complication.[24]

3.5. Associated airway pathologies

Oedema and/or haematoma may accumulate in the pharyngo-laryngeal mucosa within the first hours after trauma. Subglottic oedema tends to be circumferential, increasing the possibility of airway obstruction.[12] Air dissecting the submucosal space can further reduce the luminal diameter of the larynx and/or the trachea. Subcutaneous emphysema may induce epiglottic emphysema and reduce the supraglottic airway.[37] Straining, coughing and speaking can increase the amount of subcutaneous air and may induce intramural bleeding which can worsen airway obstruction.[12]

3.6. Associated neck or chest injuries

Airway injuries may be associated with damages to the oesophagus, vascular structures or cervical spine. Between 10% and 50% of patients with blunt airway trauma have concurrent cervical spine injuries.[38,39] A cervical spine injury should be considered present in such injuries until proven otherwise.[12] The diagnosis of a cervical injury or neurological symptoms is mandatory since this will determine the timing and surgical management of associated airway injuries.[40] Maxillofacial injuries are also common and airway obstruction may be blamed on these facial injuries.

Patients with penetrating trauma are likely to have concurrent vascular, oesophageal and thoracic injuries. Oesophageal injury occurs in 25% of patients with penetrating airway injuries, but may be missed until late in the patient's hospital course.[25]

Injuries to the chest wall, lung, and liver may be associated with crush injury to the chest.[41]

4. Diagnosis of tracheal trauma

prompt diagnosis is mandatory in order to assess the site and the extent of the airway injury; if diagnosis is delayed, the risk of complications increases. Chest X-ray is the initial imaging technique used to diagnose airway injuries. A computed tomography (CT) scan can detect over 90% of tracheal injuries resulting from blunt trauma, but bronchoscopy with a flexible bronchoscope remains the most effective approach and the gold standard technique for diagnosing, locating and determining the severity of the injury.

4.1. Clinical signs and symptoms

Any suspected airway trauma requires a meticulous evaluation of each patient for signs of these injuries, if time and circumstances allow. The broad spectrum of symptoms and clinical signs resulting from airway injuries varies according to the mechanism of injury.[12]

Clinical signs of these airway injuries are often obvious. They commonly include dyspnoea, respiratory distress, dysphonia, coughing, subcutaneous emphysema, haemoptysis, air escaping from the wound and abnormal breath sounds.

In LTT, the type of accident must be investigated and attention must be paid to signs or combinations of signs of local contusion. However, reports suggest that at least 25% of patients with LTT requiring surgical treatment have no specific physical evidence of such injury, and may not display symptoms until 48 hours after trauma.[42]

Injuries to the distal trachea and carina may present with subcutaneous or mediastinal emphysema. These signs are sometimes the only factors present, with the airway otherwise surprisingly normal.[12] Subcutaneous emphysema and/or pneumothorax may also appear. Injuries to the trachea or bronchi can rapidly prove fatal and are not always obvious on presentation. The most common clinical signs associated with blunt tracheobronchial perforations are tachypnoea, diminished breath sounds and subcutaneous and/or mediastinal emphysema.[43] Other presenting symptoms can be observed, such as pneumothorax, haemoptysis, and direct exposure of the airways. A persistent pneumothorax following tube thoracostomy or a large, continuous air leak should alert the clinician to the possibility of a TBI, prompting further investigation.[44]

4.2. Endoscopic evaluation of tracheal trauma

Endoscopic evaluation under general anaesthesia of the upper aerodigestive tract, tracheobronchial

tree and oesophagus remains the gold standard for evaluating blunt and post-traumatic tracheal lesions.

Laryngoscopy, flexible and/or rigid bronchoscopy and oesophagoscopy may be performed in order to definitively delineate the anatomy of the airway and associated injuries.[12] Bronchoscopy should be performed since both the nature and location of the injury will influence operative management. The entire tracheobronchial tree must be examined and should be completely clear of secretions and blood.[44]

Failure to recognize injuries acutely may lead to progressive airway obstruction as cicatrization takes place and stenosis develops.[12] The outcome of delayed diagnosis of associated injuries can be disastrous due to the development of life-threatening complications such as mediastinitis. Delayed diagnosis of laryngotracheal injuries is not unusual, especially when emergency intubation is performed.

4.3. Radiological findings

it is essential to insist that definitive airway management should not be delayed excessively by radiological studies, since an apparently stable airway can rapidly progress to an acute airway obstruction. Moreover, the use of sedatives for radiological assessment is not advised, since it may lead to devastating airway compromise.[12]

Angood *et al*.[38] reported that radiography alone was sufficient to diagnose 60% of patients (12 out of 20) with cervical airway trauma. However, even if plain chest radiography can be useful at the diagnosis stage, spiral CT +/- three-dimensional (3D) reconstruction may be advised for a stable patient if a supine position is possible.[45] Indeed, meticulous and prompt radiological assessment is needed to precisely locate and characterize the airway injury and to rule out associated injuries. Scaglione *et al*.[46] demonstrated that cervical and chest CT is a valuable tool for diagnosing TBI after blunt trauma, but is not mandatory after penetrating injuries.

Recent evidence indicates that multi-slice detector CT imaging with multiplanar/3D reconstruction of the images can significantly increase the diagnostic accuracy of the procedure by up to 94%–100%.[46,47]

Virtual bronchoscopy is a novel technique that comprises a computer-generated volumetric reconstruction of the tracheobronchial tree based on multiplanar/3D images obtained during multi-slice CT imaging of the airway.[11,48] This technique simulates the alternative for airway evaluation, even for the detection of TBI in selected patients with more stable airway injuries.[45,49]

Radiographic frequent signs are deep cervical emphysema, pneumomediastinum and pneumothorax. The CT may show mediastinal air, disruption of the tracheobronchial air column, deviation of the airway, or the specific site of airway disruption. CT also allows direct visualization of the TBI, including herniation of the endotracheal cuff and tracheobronchial wall discontinuity, defects or enlargements.[46] Scaglione *et al*.[46] recommend scrutinizing the junction of the cartilaginous and membranous portions of the trachea and main bronchi. Evidence in CT scans of an air leak adjacent to the main bronchi, even without direct evidence of a bronchial discontinuity, should alert the clinician to injury at this level.

A negative CT scan does not obviate the need for bronchoscopy or other diagnostic studies. CT bronchography, or virtual bronchoscopy, may be helpful in some cases.[6]

5. Tracheal trauma management

5.1. Prehospital care – airway management

The first and highest priority in case of acute tracheal injury is securing a satisfactory airway. In their retrospective review on upper airway injuries, Cicala *et al*.[19] reported that 76% of patients (35/46) had no airway management difficulties. Of this number, 25 underwent traditional endotracheal intubation, six were intubated through an obvious airway defect, and four were conservatively managed without intubation. The remaining 11 patients required emergency tracheotomy, most commonly after blunt trauma.

The specific approach to airway management will largely depend on a patient's clinical status, local resources, and the provider's experience. Regardless of the technique used, obtaining a patent airway is of paramount importance.[7,25,44,50]

Whenever possible, the patient should be allowed to breathe spontaneously. Indeed, rapid induction of anaesthesia and neuromuscular blockade can rapidly lead to apnoea, complete collapse of an already traumatized and distorted airway,[19,51] and inability to provide positive pressure ventilation. Positive pressure ventilation with a mask may

become impossible in such conditions, and may worsen subcutaneous emphysema. For this reason, spontaneous breathing should be favoured until airway safety has been established.[11]

Patients with respiratory distress and clinical suspicion of airway damage should be intubated immediately,[6] particularly in case of injury to the cervical trachea. In pre-hospital settings, the most common technique is rapid sequence intubation.

Utmost care must be taken when intubating patients with airway trauma. Indeed, attempts to blindly overpass an upper airway injury may serve to worsen the laceration and/or create a false passage for the tube.[11,52] Attempts at endotracheal intubation in patients with unsuspected cricoid injuries can be disastrous.[19] Pressure applied to a fractured cricoid may dislocate it enough to completely distort the upper airway, change the view for the physician performing the intubation, or even lead to complete airway transection and obstruction.[12] Furthermore, unsuccessful intubation of these patients can turn a partial tracheal injury into a complete transection, with catastrophic consequences.

In pre-hospital settings, tracheostomy is rare and depends on local resources. However, if endotracheal intubation appears unwise and the patient is unstable or the airway lost, immediate tracheostomy is the only appropriate choice. When the trachea itself is injured, it is preferable to try to preserve it by placing the tracheostomy through the damaged area. This will facilitate subsequent surgical repair of the trachea.[12]

5.2. Emergency department– airway management

In the emergency department, priority must be given to maintaining or improving airways in order to ensure prompt tracheal injury assessment and definitive treatment.

For stable patients with spontaneous breathing or who have been intubated in pre-hospital settings, radiological diagnosis must be completed as soon as possible and followed by endoscopic evaluation. For patients with respiratory distress and clinical suspicion of an airway injury, endoscopic evaluation and adapted intubation must be performed. Finally, patients intubated in pre-hospital settings with a mediocre respiratory status should be considered for endoscopic evaluation and airway improvement.

There are various techniques for securing the airways, including awake intubation, rapid sequence intubation, fibre-optic intubation, and a surgical approach.[44] However, induction of general anaesthesia after pre-oxygenation using a potent volatile agent and spontaneous ventilation is generally considered to be the safest way of anaesthetizing patients with possible airway injuries.[53] Use of intravenous agents like propofol may be necessary if the patient is confused or uncooperative.

Once anesthetized, the airway may be secured by passing a rigid bronchoscope or endotracheal tube into the distal airway and past the point of injury. Endobronchial intubation is sometimes required. This approach allows rigid laryngoscopy and/or bronchoscopy to be carried out, while maintaining spontaneous ventilation. These techniques may well be preferable when bleeding or debris obscure the airway, making fibre-optic examination impossible.[12] Indeed, attempts at direct laryngoscopy or intubation over a flexible bronchoscope may be futile due to bleeding within the airway or distortion of anatomic structures. There is also the danger that flexible bronchoscopy may occlude the airway or precipitate airway obstruction in patients with critical airway stenosis.[12]

As bronchoscopy is the procedure of choice for locating the site of injury as well as its extent and depth, and to ensure that the tube cuff is inflated beyond the site of damage, endobronchial intubation over a flexible bronchoscope is the preferred approach for airway management and obtaining a definitive diagnosis of TBI.[8,11,27]

Once an endotracheal tube has been placed across or distal to the site of injury, controlled positive pressure ventilation can be initiated.

In rapidly desaturating and/or haemodynamically unstable patients, it may not be possible to perform the procedure without general anaesthesia. In this case, rigid bronchoscopy may be considered, in which the patient receives inhalation induction while maintaining spontaneous ventilation. This approach allows good exposure and ventilation in an already anaesthetized patient.[11,54]

The main limitation of rigid bronchoscopy is the need to extend the neck to the shoulder, which cannot be done if cervical spine injury is suspected and has not been ruled out.[11,55]

Awake intubation appears to be an attractive approach, but can be problematic in unstable and hypoxic patients with poorly visualized vocal cords. Rapid sequence intubation provides a more controlled setting, but requires an experienced

provider. Once a neuromuscular blocker is administered, there is no more spontaneous ventilation and it becomes critical to secure the airway. Fibre-optic intubation has the advantage of direct visualization of the vocal cords and precise placement of the endotracheal tube. Establishing a surgical airway is another technique that should be considered in case of near transection of the cervical trachea.[44]

Injuries to the carina and main bronchi are challenging for airway management, since blind endotracheal intubation and positive pressure ventilation may increase air leaks and lead to severe respiratory insufficiency and pending respiratory arrest.[11,56] The tube can be guided into the uninjured bronchus in case of bronchial rupture, or a double-lumen tube may be used to intubate the patient.[11,57] For patients suffering from post-intubation TBI to the distal trachea, placing low-pressure cuffed tubes into both bronchi through the tracheostomy has been reported.[11,58]

In case of absolute emergency, thoracotomy and placement of intrabronchial catheters in both bronchi through the chest wound may allow adequate ventilation in patients with distal airway injuries, who continue to rapidly desaturate despite application of standard airway management procedures.[11]

Tracheostomy is not routinely performed for airway trauma. It should only be done under local anaesthesia in patients with significant LTT, involving complete or pending airway obstruction, or when endotracheal intubation is considered unsafe, such as in the presence of concomitant craniomaxillofacial injuries.[12,59] It should, however, be performed in all patients with TBI after failed attempts at endotracheal intubation.[11,60,61]

In patients with penetrating cervical tracheal injuries, insertion of a tracheostomy tube through the wound is the best way of securing the airway and saves tissue for future repair if deemed necessary.[54]

5.3. Definitive therapeutic management

The ideal therapeutic approach to tracheal lesions is a matter of debate. Once post-traumatic injury to the airway is diagnosed by clinical, radiologic and bronchoscopic assessment, effective treatment is essential to prevent septic complications that could compromise the outcome.[3]

Although surgery is traditionally recommended as the treatment of choice,[7,62] recent reports have demonstrated the efficacy of conservative management,[63] especially in patients with iatrogenic lesions.[58,64] Indeed, lesions caused by intubation or tracheotomy are usually simple longitudinal lacerations of the membranous tracheal wall, possibly covered with the surrounding tissues[3] and showing spontaneous healing. In contrast, patients with airway injuries due to blunt or penetrating trauma often have complex lesions and require specific management to achieve prompt and stable airway control. For these patients, surgical treatment is often indicated. A conservative approach should be reserved for minor injuries or when poor medical conditions contraindicate surgery.[3]

Kiser *et al*.[16] reported better survival in patients treated with surgery than those following conservative management. In a study by Carretta *et al*., 71% of patients with airway lesions caused by blunt or penetrating trauma underwent surgical treatment, compared to 55% of patients with iatrogenic lesions.

5.3.1. Surgery

Surgical management is determined by the site and extent of injury, and the associated injuries. The rationale for surgery, as proposed by Prokais *et al*.,[11] is to close airway defects in order to improve ventilation, prevent mediastinal spillage and infection, and avoid spontaneous healing complications that could lead to airway stenosis and recurrent pulmonary infections.

In a recent paper, O'Connor[44] highlighted several important principles to bear in mind when considering a surgical approach. Firstly, there must be precise coordination with the anaesthesia team. Generally, a single-lumen endotracheal tube is sufficient, but when placing tracheal repair sutures, it may be necessary to briefly hold ventilation. Secondly, it is important to consider the tracheal blood supply which, unlike the oesophagus, is segmental, arising from the inferior thyroid and bronchial arteries. With a segmental blood supply, it is important to limit circumferential dissection, thus avoiding ischaemia, especially at the vulnerable suture line. Thirdly, repair techniques include the meticulous placement of interrupted non-absorbable sutures, which are all placed prior to being sequentially tied. Larger circumferential injuries may require debridement before repair. After tying the sutures, the anaesthesia team must gently manipulate the endotracheal tube to ensure

it has not been incorporated into the suture line. Finally, associated injuries are repaired as they would be if they were isolated injuries. Interposing viable muscle, typically intercostal, between adjacent suture lines (trachea and oesophagus, trachea and artery) is vital to prevent development of a potentially fatal fistula between adjacent structures.

Following surgery, intraoperative bronchoscopy is performed to assess the repair. Extubation is advisable immediately following repair. There is no role for routine tracheostomy or prolonged intubation to 'stent the repair'. A natural airway with high humidification is recommended after surgery.

When surgery is performed early after the injury, the long-term outcome is good for over 90% of the patients.[27] The 30-day mortality varies from 0% to 44.4% [3,8,10,62] and is primarily affected by the presence of concomitant injuries, the time between diagnosis and treatment and the need for pneumonectomy.[11]

5.3.1.1. Surgical approach according to the site of injury

For lesions of the proximal two thirds of the trachea, the standard approach remains the transverse or left cervicotomy with upper third sternotomy if further exposure is necessary. This approach also provides an excellent exposure to vascular or oesophageal injuries in the neck. Incision over the manubrium and splitting the manubrium down to the second interspace opens the thoracic inlet and provides a broader exposure to the middle third of the trachea,[7,65-67] as well as proximal control of the innominate artery or veins.[6]

Posterior tracheal wall lacerations can also be treated via left cervicotomy or collar incision followed by longitudinal tracheotomy to reach the membranous wall.[67] Angelillo-Mackinlay[68] and Lancelin[69] *et al*. proposed a transtracheal-transcervical endoluminal repair procedure for membranous tracheal injuries in order to avoid tracheal ischaemia and recurrent nerve injury.

Combined tracheal and oesophageal injuries are usually approached through a unilateral left incision.[70]

Injuries to the lower third of the trachea, the carina and mainstem bronchi usually require a classical right thoracotomy, at the fourth intercostal space, to provide a good exposure to these structures and to the azygous vein, superior vena cava, right atrium, and to the entire intrathoracic oesophagus, and to achieve an optimal exposition and reparation of the defect. The alternative includes median sternotomy followed by posterior transpericardial access to the airway once the ascending aorta and the superior vena cava have been mobilized.

Finally, abruptions of the left bronchus close to the bifurcation of the lobar bronchi are best treated via left thoracotomy.

5.3.1.2. Surgical repair according to the extent of injury

Longitudinal lesions are preferably repaired directly with absorbable sutures, whereas transverse lesions, which occur more frequently after blunt or penetrating trauma, are repaired using end-to-end anastomoses performed according to standard airway reconstructive surgery techniques.[71]

Small tears and lacerations should be closed with direct sutures, while complete or partial transections require debridement of the infected and devitalized tissues, trimming of the edges of the injured airway and end to end anastomosis.[11]

The repair should be done with absorbable sutures with the knots tied on the outside to avoid the development of granulomas that may protrude into the airway lumen.[66,72]

In combined trachea-oesophageal injuries, the sutures may be covered by protective tissue such as pericardium, muscle flaps, pleura or mediastinal fat.[7,9,73]

When resection is necessary, a tension-free anastomosis can be performed by flexing the neck before the repair. This flexion must be maintained post-operatively, using chin-to-chest stitches, during the first days following surgery. Other alternatives include laryngeal release manoeuvres, division of the inferior pulmonary ligaments and pericardial release of the pulmonary hilum.[11]

If there is extensive tissue damage and a large defect precluding primary repair, an end tracheostomy must be created. The proximal trachea is closed and the distal one is circumferentially sewed to the skin. An attempt at definitive repair can be performed later on.[11,54]

Bronchial injuries are treated by applying the same principles. However, extensive bronchial damage, co-existing pulmonary vascular injuries, and/or irreversible destruction of lung parenchyma may necessitate lung resection for the effective control of the injury.[65,74]

5.3.2. Conservative management

A conservative treatment must be discussed for small injuries, primarily mucosal, which are not associated with a significant, on-going air leak or distal obstruction. These lesions typically are smaller than one third of the entire circumference and should not be associated with tissue devitalization. These injuries still require follow-up, as late stricture and related complications can occur.[6]

Several studies have demonstrated the possibility of non-operative management in patients with post-intubation tracheal lacerations.[58,75,76] Indications for conservative or surgical treatment were based on clinical and endoscopic findings. Conservative management of acute tracheal injuries should be considered for selected cases; the stability of the patient is a prerequisite. Ross *et al*.[63] suggested that non-operative management of intubation-related tracheal laceration should be considered for patients with stable vital signs, without ventilation difficulty and without evidence of oesophageal injury, mediastinal fluid collection, progressive pneumomediastinum or subcutaneous emphysema and signs of sepsis.

In a recent review, Minambres *et al*.[64] reported on 71 patients with post-intubation tracheal rupture who underwent conservative treatment. Mortality rate among these patients was 14.5%, compared to 30.4% for the remaining 111 patients who underwent surgical repair.

5.3.3. Airway management in the case of blunt ltt in children

Initial airway management in children with suspected laryngotracheal injuries remains controversial. The incidence of such injuries is lower in children than in the adult population.[77,78] Anatomically, the paediatric larynx is located higher in the neck, allowing the mandibular arch to protect the larynx.[77,79-81] In addition, the laryngeal cartilages are more flexible in children, decreasing the probability of laryngeal fractures. However, the narrower lumen of the paediatric airway and loose attachment of the mucosa to the underlying laryngeal cartilages in children increases the risk of soft tissue damage, oedema, and haematoma formation, resulting in airway obstruction. [77,79-81]

The aetiology of blunt neck trauma in children is age-dependent. In younger children, common aetiologies include falls onto furniture or bicycle handlebars with the neck extended, causing compression of the larynx and trachea against the vertebral column.[77,79-81] Among adolescents, the aetiology is similar to adults and includes motor vehicle accidents, sports injuries, and "clothesline" injuries.[79]

There is little information in the literature to guide initial management.[79] Early consultation with appropriately experienced clinicians at the closest paediatric trauma centre is strongly advised, if possible. The decision to perform rapid sequence induction depends on the experience of pre-hospital providers and needs to be weighed against the possibility of aggravating the injury.[80] If a patient's airway is stable, a detailed history should be taken and a physical examination performed, followed by flexible fibre-optic laryngoscopy at the bedside to evaluate the extent of injury. Conservative management includes administration of humidified air and systemic corticosteroids, close observation in a monitored setting, and serial bedside endoscopy.[79] If the patient's clinical condition deteriorates, or in subjects who present with acute respiratory distress, the airway is ideally secured after induction of general anaesthesia under bronchoscopic guidance.

6. Inhalation airway injuries - diagnosis and management

6.1. Inhalation airway injuries - diagnosis

A diagnosis of inhalation injury is subjective, and is made on the basis of clinical findings. Pertinent information includes exposure to flames, smoke or chemicals, duration of exposure, exposure in an enclosed space, and loss of consciousness or disability.[24] Meticulous physical examination must investigate any facial burns, carbonaceous material on the face or in the sputum, and signs of airway obstruction.[82] Cyanide poisoning must be suspected in smoke inhalation victims in the case of soot on the face or in the mouth, nose or expectorations.[83]

A number of diagnostic modalities are available to confirm inhalation injury, including fibre-optic bronchoscopy (FOB), chest CT, carboxyhaemoglobin measurement, radionuclide imaging with xenon-133, and pulmonary function testing.[24]

FOB is a valuable tool, but is unable to assess distal airways and respiratory bronchioles. Despite these limitations, it continues to be the standard

technique used to evaluate the presence and severity of inhalation injury.[24] In the case of suspected inhalation injury, FOB should be repeated after 24–48 hours if negative at the initial assessment. The Abbreviated Injury Scale scoring system for inhalation injury detected by bronchoscopy has been shown to correlate with an increase in mortality rates, as well as impaired gas exchange:[24,84]

0 = No injury: absence of carbonaceous deposits, erythema, oedema, bronchorrhoea, or obstruction.

1 = Mild injury: minor or patchy areas of erythema, carbonaceous deposits, bronchorrhoea, or bronchial obstruction.

2 = Moderate injury: moderate degree of erythema, carbonaceous deposits, bronchorrhoea, or bronchial obstruction.

3 = Severe injury: severe inflammation with friability, extensive carbonaceous deposits, bronchorrhoea, or obstruction.

4 = Massive injury: evidence of mucosal sloughing, necrosis, and/or endoluminal obstruction.

Endorf *et al*.[82] showed that patients with an arterial partial pressure of oxygen (PaO2)/ fraction of inspired oxygen (FiO2) ratio <350 upon presentation had significantly increased fluid resuscitation needs compared with patients with a ratio >350 (p=0.03). Ryan *et al*.[85] found the most reliable indicator of the impact of inhalation injury to be the PaO2/FiO2 ratio once resuscitation is started. Hassan *et al*.[86] proposed using the PaO2/FiO2 ratio as a predictor for survival upon completion of initial burn resuscitation. However, it is important to note that PaO2/FiO2 can be arbitrarily high or low depending on the choice of ventilator mode.[24] Moreover, PaO2/FiO2 may be affected by the volume of resuscitation. Walker *et al*.[24] therefore suggested that PaO2/FiO2 should not be used as a basis for diagnosing inhalation injury; instead, a patient's oxygenation status and potential need for nonconventional ventilation should be followed.

Other means of evaluating the severity of inhalation injury include chest CT, whereby the radiologist scores the severity of the CT scan findings (RADS score), as proposed by Oh *et al*.[87]:

0 = Normal.

1 = Increased interstitial markings.

2 = Ground-glass opacification.

3 = Consolidation.

Yamamura *et al*.[88] used CT imaging to measure bronchial wall thickness 2 cm distal to the tracheal bifurcation in patients with inhalation injuries. The authors noted a statistically significant correlation between bronchial wall thickness and the development of pneumonia, total number of ventilator days, and length of stay in intensive care units.[24] They also found that bronchial wall thickness of >3.0 mm predicted the development of pneumonia.

6.2. Inhalation airway injuries - management

The first step in the case of inhalation airway injury is to provide prompt and supportive respiratory care.[24] This involves pulmonary hygiene and mechanical ventilation, if indicated. About one third of patients hospitalized with inhalation injury experience some degree of upper airway obstruction due to pharyngolaryngeal oedema, which can progress rapidly[24,89] and sometimes requires early intubation.[23] In most cases, endotracheal intubation is advised for patients with suspected or impending upper airway obstruction in the context of inhalation injury.[24]

Intravenous infusion of hydroxocobalamin (Cyanokit®) should be administered as soon as possible to patients exposed to smoke or chemicals in an enclosed space, particularly with clinical evidence of soot around the face, mouth or nose and signs of neurological impairment. Indeed, Borron *et al*.[83] demonstrated that administration of hydroxocobalamin at the scene of the fire was associated with survival in 67% of patients confirmed a posteriori to have suffered cyanide poisoning. Hydroxocobalamin therefore appears to be suitable for pre-hospital management of acute cyanide poisoning caused by smoke inhalation.[83,90] A standard dose of 5 g is infused intravenously over the course of 15 minutes, with a second dose of 5 g possibly required in patients with severe toxicity or poor clinical response.[24]

6.2.1. Respiratory support

Once patients with inhalation injury are stabilized, maintenance of bronchial hygiene must be ensured by early ambulation, chest physiotherapy, airway suctioning and therapeutic bronchoscopy.[89] Intrapulmonary percussive ventilation administered through a face mask to spontaneously breathing patients with smoke inhalation injury, hypoxia and/or atelectasis has been shown to significantly improve the PaO2/FiO2 ratio.[91]

Mechanical ventilation may be a significant contributor to mortality in burn patients with inhalation injury. However, in order to apply lung-protective ventilation in patients with inhalation injury, non-conventional ventilator modes need to be used.[24]

Prophylactic high-frequency percussive ventilation (HFPV) has proved beneficial in both adult[92,93] and paediatric[94] populations. Cioffi et al.[92] demonstrated that the use of HFPV was associated with a drop in the incidence of pneumonia from 45% to 26% ($p<0.005$) and yielded improved survival rates.

Walker *et al*.[24] reported that use of HFPV significantly increased the PaO2/FiO2 ratio on days zero to three compared to conventional low tidal volume (LTV), and that fewer patients in the HFPV cohort required conversion to a rescue mode of ventilation than in the LTV ventilation cohort.[95]

For paediatric populations, high tidal volume (HTV) ventilation must be considered, since it is associated with increased maximum peak inspiratory pressure and shortens the time needed on the ventilator.[96] HVT ventilation may be more effective for paediatric patients than traditional LTV ventilation; however, further randomized trials are required to confirm this hypothesis.

For burn patients with acute hypoxaemic respiratory failure, the use of extracorporeal membrane oxygenation (ECMO) remains the definitive rescue treatment, even if its application after inhalation injury is limited by the small number of studies conducted.[24]

6.2.2. Associated therapy

6.2.2.1. Hyperbaric oxygen therapy

Carbon monoxide (CO) toxicity has deleterious effects on haemoglobin levels and, more specifically, capacity for oxygen delivery. Symptoms of CO poisoning include confusion, coma, seizures, and myocardial infarction.[24] CO diagnosis requires the use of a CO-oximeter, since carboxyhaemoglobin (COHb) levels may be elevated despite normal PaO2 and oxygen saturation readings. Treatment of CO poisoning involves providing 100% oxygen, which shortens the half-life of COHb to about 45 minutes, and hyperbaric oxygen therapy (HBOT).[24]

6.2.2.2. Bronchodilating agents

Beta2-adrenergic agonists and muscarinic receptors decrease airflow resistance and improve dynamic compliance. There is also evidence that both beta-agonists and muscarinic receptor antagonists may mitigate the host inflammatory response. Moreover, both muscarinic and adrenergic receptors are found on respiratory epithelial gland cells and may enhance regeneration and healing following injury.[24]

6.2.2.3. Mucolytic agents

N-acetylcysteine (NAC) is a powerful mucolytic that helps loosen up thick airway secretions. It may play a role in mitigating ROS.[24] However, patients are often pre-dosed with a bronchodilating agent, since NAC may irritate the airway and cause bronchoconstriction.[89]

6.2.2.4. Inhaled anticoagulants

Inhaled anticoagulants, such as heparin, heparinoids, antithrombin and fibrinolytics, have been shown to improve survival and decrease morbidity in preclinical and clinical studies of inhalation injury.[97] These agents, combined with NAC, encourage the formation of fibrin casts and prevent airway obstruction after inhalation injury.[24]

7. Complications

Although complications may be seen in up to 25.8% of patients with tracheal damage,[65] major morbidity is mostly related to septic complications from long-term intensive care unit recovery and anastomotic dehiscence.[8,11,62,74,98]

Mortality rates are variable and influenced by the presence of associated injuries, especially vascular. Mortality from isolated penetrating cervical tracheal injuries stands at 3.5%,[13] while from blunt injury the rate is higher, at 13.5%. Regardless of mechanism, associated vascular injury increases mortality (21%).[99] A blunt mechanism, need for a surgical airway, missed oesophageal injury, and the presence of a vascular trauma are all associated with higher mortality. Complications are rare and often related to the associated injuries. The most feared tracheal complication is stenosis, which can usually be managed by dilation. Long-term complications include airway stenosis[65] and dysphonia from injuries to the larynx and recurrent laryngeal nerves.[100]

The outcome due to delayed diagnosis of associated injuries such as oesophageal perforation can be devastating, due to the development of life-

threatening complications such as mediastinitis. Delayed diagnosis of laryngotracheal injuries is not unusual, especially when emergency intubation is performed.[101]

The most common complications following inhalation injury are respiratory tract infection and pneumonia. These are the consequences of thermal injury, inflammatory response, damaged ciliated cells and impaired surfactant production.[24] Empiric antibiotics should be administered immediately in any case of suspected respiratory infection, and later modulated based on the sputum culture.

Upper airway stenosis is also commonly reported in inhalation injuries, since thermal injuries occur at this site and contribute to the development of scar tissue during healing. Tracheal stenosis, endobronchial polyps, bronchiectasis, bronchiolitis obliterans, laryngeal synechia and dysphonia have also been reported.[24]

8. Conclusions

Tracheal injuries are rare and result from blunt, penetrating or inhalation mechanisms. Injuries involving the cervical or thoracic trachea significant associated injuries. An understanding of the mechanism of injury and the signs and symptoms, especially the degree of respiratory compromise, are essential to the clinical evaluation. The rapid achievement of a secure airway is crucial. The location and extent of the injury is visualized by bronchoscopy and CT. Proximal injuries are approached through a collar incision, while almost all distal injures are approached using a right posterolateral thoracotomy. Precise suture placement and intra-operative airway management are integral to a successful outcome. Immediate post-repair bronchoscopy and early extubation are essential. Concomitant injuries are managed as they would be if they were isolated, with the addition of a muscle buttress between adjacent suture lines. By following these principles, gratifying results can be obtained with TBI.[44]

9. Take-home messages

Pre-hospital and emergency management

1. Blunt injuries to the airways must be considered after direct blows, severe flexion/extension damage, or crush injuries to the neck or chest, especially after vehicle crash or strangulation.

2. Tracheal injury after penetrating trauma most often involves the cervical trachea.

3. Clinical signs of airway injuries include dyspnoea, respiratory distress, dysphonia, coughing, subcutaneous and/or mediastinal emphysema, haemoptysis, air escaping from the wound and abnormal breath sounds.

4. The first and highest priority in case of acute tracheal injury is the securement of a satisfactory airway.

5. Whenever possible, the patient should be allowed to breathe spontaneously.

6. Patients with respiratory distress and clinical suspicion of airway damage should be intubated immediately, particularly in the case of injury to the cervical trachea.

7. In patients with penetrating cervical tracheal injuries, insertion of a tracheostomy tube through the wound is the best way of securing the airway and saves tissue for future repair if deemed necessary.

8. Tracheostomy is not routinely performed for airway trauma. It should only be done under local anaesthesia in patients with significant LTT, involving complete or pending airway obstruction, or when endotracheal intubation is considered unsafe, such as in the presence of concomitant craniomaxillofacial injuries. It should, however, be performed in all patients with TBI after failed attempts at endotracheal intubation.

9. A persistent pneumothorax or a large, continuous air leak should alert the clinician to the possibility of a TBI.

10. Multi-slice detector CT imaging with multiplanar/3D reconstruction of the images can significantly increase diagnostic accuracy.

11. Bronchoscopy is the procedure of choice for locating the site of injury as well as its extent and depth, and to ensure that the tube cuff is inflated beyond the site of damage.

12. For stable patients with spontaneous breathing or who are intubated in pre-hospital settings, radiological diagnosis must be completed as soon as possible and should be followed by endoscopic evaluation.

13. For patients with respiratory distress and clinical suspicion of an airway injury, endoscopic evaluation and adapted intubation must be performed.

14. For patients intubated in pre-hospital settings with a mediocre respiratory status, endoscopic evaluation and airway improvement must be considered.

15. General anaesthesia is induced after preoxygenation using a potent volatile agent, and spontaneous ventilation is preferred.

16. Once anaesthetized, the airway may be secured by passing a rigid bronchoscope or endotracheal tube into the distal airway and past the point of injury.

17. Inhalation injury necessitates early intubation in most cases due to rapid development of upper airway oedema.

18. The first step in case of inhalation injury to the airway is to provide prompt and supportive respiratory care. This involves pulmonary toilet and mechanical ventilation if indicated.

19. Intravenous infusion of hydroxocobalamin (Cyanokit®) should be administered as soon as possible to patients exposed to smoke or chemicals in an enclosed space, with clinical evidence of soot on the face, mouth or nose and with neurologic impairment.

Definitive management

1. Effective treatment is essential to prevent septic complications.

2. Surgery is traditionally recommended as the treatment of choice for traumatic tracheal injury.

3. A conservative approach should be reserved for patients with iatrogenic lesions, minor injuries or when poor medical conditions contraindicate surgery.

4. For lesions of the proximal two thirds of the trachea, the standard approach remains the transverse or left cervicotomy, with upper third sternotomy if further exposure is needed.

5. Posterior tracheal wall lacerations can also be treated via left cervicotomy or collar incision followed by longitudinal tracheotomy to reach the membranous wall.

6. Injuries to the lower third of the trachea, the carina and mainstem bronchi usually require a classical right thoracotomy.

7. Abruptions of the left bronchus close to the bifurcation of the lobar bronchi are best treated via left thoracotomy.

8. Longitudinal lesions are preferably repaired directly with absorbable sutures, whereas transverse lesions, which occur more frequently after blunt or penetrating trauma, are repaired using end-to-end anastomoses.

9. At the end of surgery, intraoperative bronchoscopy is performed to assess the repair. Extubation is advisable immediately following repair.

10. Mechanical ventilation, associated with bronchodilating, mucolytic and inhaled anticoagulants, is the treatment of choice for burn patients with inhalation injury.

9. List of abbreviations

LTT : Laryngotracheal trauma
TBT : Tracheobronchial trauma
TBI : Tracheobronchial injury
CO_2 : Carbon dioxide
CO : Carbon monoxide
NOS : Nitric oxide synthase
ROS : Reactive oxygen species
CT : Computed tomography
3D : Three-dimensional
FOB : Fibre-optic bronchoscopy
PaO2 : Arterial partial oxygen pressure
FiO2 : Fraction of inspired oxygen
RADS : Radiologists' scoring table
HFPV : High-frequency percussive ventilation
LTV : Low tidal volume
HTV : High tidal volume
COHb : Carboxyhaemoglobin
ECMO : Extracorporeal membrane oxygenation

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