Imaging Evaluation of Tracheobronchial Injuries

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SA-CME LEARNING OBJECTIVES

After completing this journal-based SA-CME activity, participants will be able to:

- Explain how the mechanism of injury affects the distribution of tracheobronchial injuries.
- Describe the typical imaging features of tracheobronchial injury.
- Discuss how the imaging features of tracheobronchial injuries affect management and treatment.

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Tracheobronchial injuries are a rare but potentially life-threatening cause of respiratory insufficiency, with high mortality rates. For patients with potentially survivable tracheobronchial injuries, imaging in the acute setting plays a key role in demonstrating the injuries and associated complications. The radiologist can improve outcomes by understanding typical injury patterns according to injury mechanism and the influence that imaging findings may have on treatment decisions. Chest radiography and cervical and thoracic CT are the mainstays of imaging in the acute setting and in follow-up, often as part of a whole-body trauma imaging series. The authors first consider the influence of normal tracheobronchial anatomy with regard to protective features, such as cartilaginous rings. They also discuss inherent points of vulnerability, such as points of relative fixation at the carina. A framework is then provided for understanding the typical distribution and morphology of tracheobronchial injuries according to cause. This includes penetrating, iatrogenic, and blunt force mechanisms, with consideration of potential complications. The authors highlight treatment strategies that require multidisciplinary collaboration, such as ventilation, minimizing injuries, and defining optimal surgical or nonsurgical treatment.

Introduction

Traumatic tracheobronchial injuries are rare, but they can be life threatening or cause significant morbidity. In part, this is because the majority of noniatrogenic tracheobronchial injuries are associated with other significant injuries or comorbidities (1). It is estimated that 30%–80% of patients with tracheobronchial injuries die before arrival at an emergency department (1,2). Despite survival rate improvements in recent years, mortality among patients who reach hospital care remains as high as 23% (1).

Radiologists are likely to encounter increasing numbers of iatrogenic tracheobronchial injuries because of better emergency care enabling more acutely injured patients to undergo CT. They are also likely to perform adjunct imaging in known airway injuries to assist the growing implementation of interventional airway procedures worldwide (3).

Bronchoscopy remains the gold standard for imaging tracheobronchial injury. Diagnostic imaging is usually performed with CT at an earlier stage in the acute setting, and it is often used to help select patients for bronchoscopic evaluation. CT has the advantage of being fast and noninvasive, and it demonstrates extratracheal injuries in the context of major trauma, including major vessels and pulmonary and musculoskeletal damage.

Nonetheless, it can be challenging to identify tracheobronchial injury in the early stages of assessment in the acute setting. The precise site of injury is frequently subtle or occult at imaging, even in the presence of other suggestive imaging features such as pneumomediastinum,

TEACHING POINTS

- The precise site of injury is frequently subtle or occult at imaging, even in the presence of other suggestive imaging features such as pneumomediastinum, pneumothorax, or deep cervical subcutaneous emphysema.
- Penetrating injuries such as stabbings are more commonly found in the anterior cervical trachea because of its relatively exposed position. Iatrogenic injuries such as those related to bronchoscopic procedures most commonly affect the cervical and proximal intrathoracic trachea, especially the less protected posterior membrane. High-impact blunt force injuries tend to involve the intrathoracic distal trachea near the carina, with a slight preponderance of right-sided involvement.
- Endotracheal intubation usually causes cuff-related injuries rather than direct lacerations. Cuff overinflation can be depicted at CT or radiography by a discrepancy in cuff diameter relative to the adjacent trachea.
- Surgery is usually performed in lacerations greater than 2–4 cm, especially when there is involvement of the cartilage. Surgery may also be performed in patients with worsening pneumomediastinum, subcutaneous emphysema, or pneumothorax or with a lung that fails to re-expand despite drain placement. Mediastinal sepsis and proximity of the injury to the carina have also been proposed as indications for surgery. Emergency surgery is required where there is failure to ventilate or if there is esophageal herniation through the tracheal defect, which may be visualized at CT.
- In more borderline cases with lacerations measuring 1.5–2 cm or less, there is increasing momentum behind nonsurgical management options. These include rigid and flexible bronchoscopic application of synthetic adhesives (fibrin- or cyanoacrylate-based), which may be considered in injuries smaller than 5 mm, and covered metallic or silicone stent placement, both of which have shown promising results in specialist units.

pneumothorax, or deep cervical subcutaneous emphysema. Radiologists may overlook tracheobronchial injuries, particularly in instances where more overt thoracic or cervical injuries are also present.

In one small retrospective study, the diagnosis of major tracheobronchial injury was not made or suggested at the initial neck or thorax CT examination in two of 13 (15%) of subsequently clinically confirmed cases (4). However, identification of tracheobronchial injury at imaging can be critical to help guide decisions on intubation, ventilation, and further surgical or conservative treatment. It plays an integral part in preventing further airway and ventilation deterioration. The ultimate goals of early identification of tracheobronchial injury at imaging are to prompt appropriate treatment to secure the airway and to reduce the risk of complications.

After a brief review of relevant tracheobronchial anatomy, this article provides an overview of common patterns of traumatic injury according to the mechanism. Injuries are categorized broadly as penetrating, iatrogenic, or blunt force. The main acute, medium-term, and long-term complications are then considered, including pneumomediastinum, pleural fistulation, infection, and stricturing. The final section discusses imaging features that may help guide acute treatment, particularly relating to intubation and ventilation and surgical and nonsurgical techniques.

Tracheobronchial Anatomy

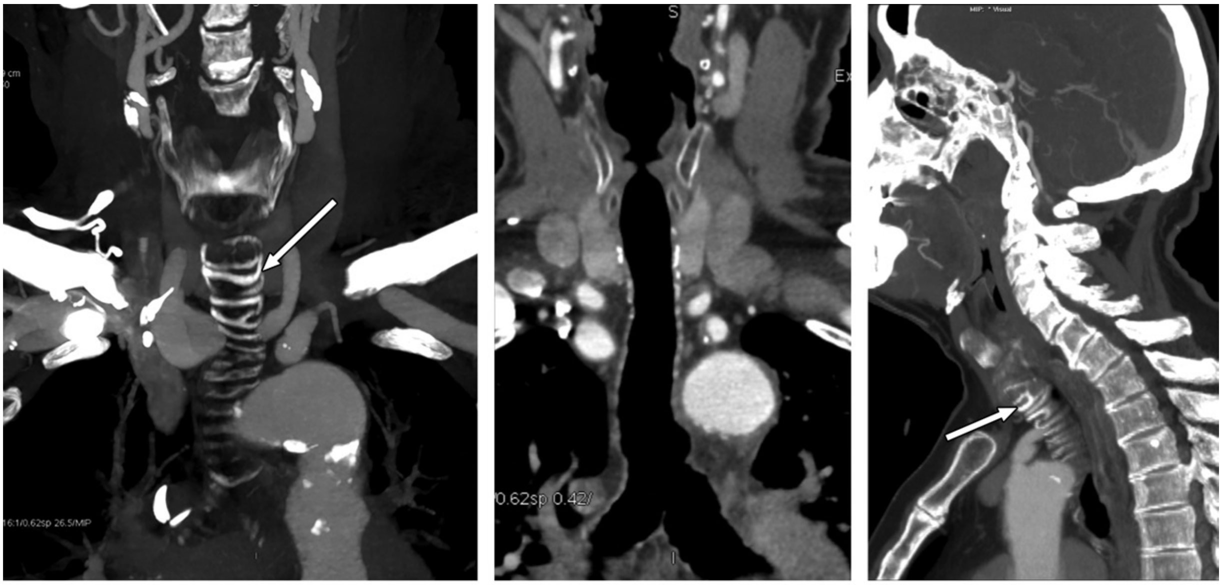
Knowledge of tracheobronchial anatomy aids understanding of the typical patterns of injury seen at imaging. Central airway protective features include the obliquely angulated anterior cartilaginous rings extending from the cervical trachea to the carina (Fig 1).

In our experience and that of other reports (5), a penetrating implement oriented in the axial plane has a greater risk of passing between the cartilaginous rings than a sagittally oriented implement, more frequently resulting in significant injury (Figs 2,3). A degree of further mechanical reinforcement is provided by adjacent left-sided mediastinal structures, most significantly the aorta, and this is thought to account for a slight preponderance of right-sided injuries in cases of blunt trauma (6). In addition, the proximity of the right main bronchus and distal trachea to the vertebral column has been postulated as a predisposing factor to injury in this location in cases of blunt trauma because of compression of these structures against the vertebrae (7).

The posterior membrane of the trachea is inherently more vulnerable to direct trauma than the stronger anterior cartilaginous rings. This is of particular importance in iatrogenic injuries, when it can be subject to laceration. Therefore, the radiologist should carefully inspect the posterior membrane.

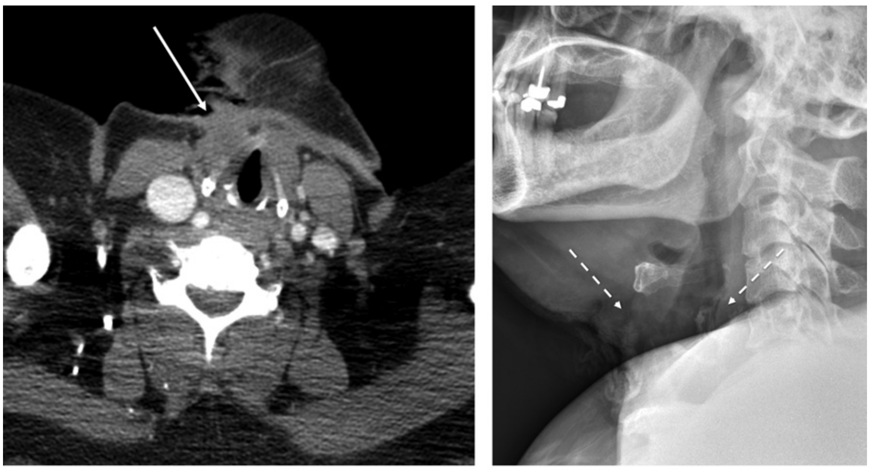
The posterior membrane is also vulnerable to the indirect consequences of tracheobronchial injury, as it can become compressed by external pressure from large-volume pneumomediastinum, causing progressive airway compromise. Consideration should also be given to the vulnerability of the cricotracheal membrane in the region of the laryngotrachea. This can be injured in blunt force cervical injuries and can lead to laryngotracheal separation.

The asymmetry of the left and right main bronchi causes different typical patterns of traumatic abnormality to appear at imaging. Right main bronchus injuries typically manifest with pneumomediastinum and associated pneumothorax because of free communication with the pleural space. In right main bronchus injuries that necessitate surgical intervention, the surgeon typically repairs the right main bronchus after selective intubation of the left main bronchus. By contrast, left main bronchus injuries typically manifest with pneumomediastinum alone



a. b. c.

Figure 1. Normal tracheal anatomy. Multiple tracheal cartilaginous rings extend from the cervical region to the carina. Coronal **(a)**, coronal oblique **(b)**, and sagittal **(c)** maximum intensity projection (MIP) CT reformations highlight normal tracheal anatomy. These rings (arrow in **a** and **c**) provide anterior and lateral reinforcement in trauma to maintain and protect the open airway. The oblique orientation of the rings relative to the axial plane provides additional strength.



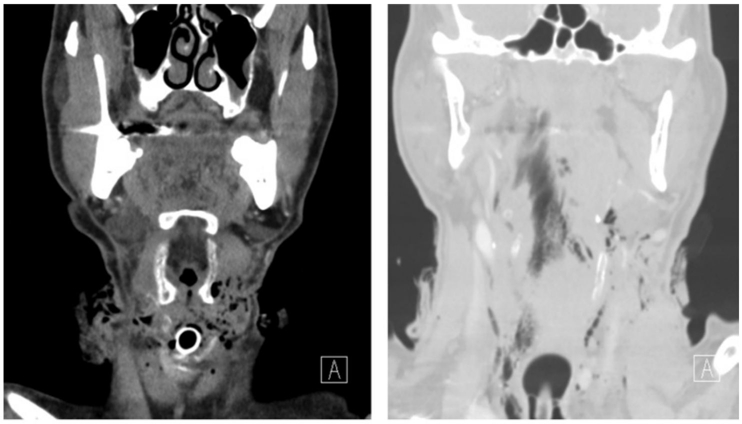
a. b.

Figure 2. Stabbing injury with limited damage to the trachea. The oblique axial orientation of cervical tracheal cartilage rings provides a degree of protection against penetrating injuries in the sagittal plane. Axial CT image (soft-tissue window) at the level of the larynx **(a)** and lateral soft-tissue radiograph of the larynx and proximal trachea **(b)** obtained after a sagittal-orientation stabbing injury show superficial soft-tissue laceration and subcutaneous small hematoma (arrow in **a**) and relatively limited subcutaneous emphysema (arrows in **b**). There was no significant tracheal injury.

because the proximal 4 cm of the left main bronchus are located in the mediastinum. Left main bronchus injuries tend not to deteriorate as quickly as right main bronchial injuries, but selective intubation typically becomes more challenging because of progressive pneumomediastinum, which can compress the membranous portions of the tracheobronchial tree.

Tracheobronchial anatomy and injury are most commonly and optimally demonstrated with CT. Thin-section (eg, 1-mm) axial reconstructions are the most heavily relied on reformations in the acute setting. It is important to recognize that tracheobronchial injury may be subtle, and it may be visible only on a single image section.

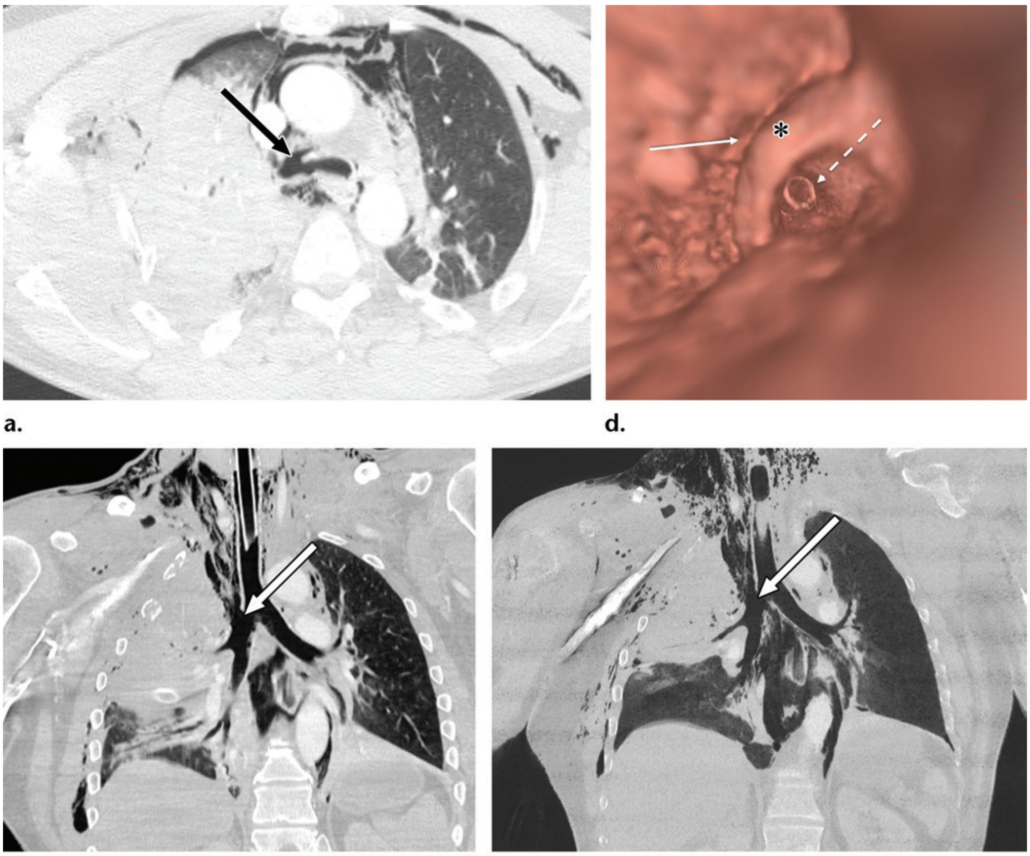
Indeed, the precise location of injury may not be visible at imaging, even in the context of extensive nonanatomic gas in a suggestive clinical setting. Delayed manifestations of tracheobronchial rupture may occur. It is common for the site of injury to become evident at imaging in retrospect, when complications such as stricturing occur. This is especially relevant to more peripheral bronchial injuries, which are less common and more difficult to diagnose because of the smaller airway size. Where possible, the radiologist describes the level and size of the tracheobronchial injury. Providing the diameter of the left and right main bronchi may also help the anesthesiologist choose an appropriate tube size in patients who require selective intubation.



a. b.

Figure 3. Significant tracheal injury that required emergency tracheostomy. The cervical trachea is particularly vulnerable to axial orientation penetrating injuries, which may pass between cartilage rings. Coronal soft-tissue window **(a)** and lung window **(b)** CT images demonstrate more extensive deep cervical emphysema and hematoma after a stabbing in the axial orientation.

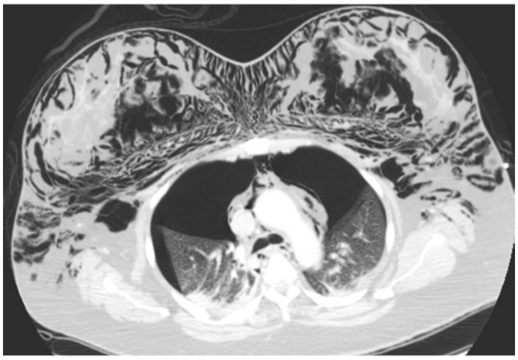
Figure 4. Advanced reformations in a patient who was involved in a blunt force road traffic accident. **(a)** Axial 1-mm-thick lung window CT image shows a defect in the proximal right main bronchus at the carina (arrow). **(b)** Coronal oblique CT reformation displays the defect more strikingly (arrow). Large-volume pneumomediastinum, deep cervical emphysema, small pneumothoraces, displaced rib fractures, and extensive right upper lobe contusion are also shown. **(c)** Coronal oblique lung window minimum intensity projection CT image shows the injury (arrow). **(d)** Virtual bronchoscopic image viewed from below may also elegantly demonstrate the injury, but these images are more time-consuming to acquire and are seldom obtained in the acute setting. The tip of the endotracheal tube is visible centrally (dashed arrow), with an exposed tracheal ring (*) adjacent to the defect. Extensive pneumomediastinum is shown laterally (solid arrow).



a. d. b. c.

Multiplanar reformations, particularly those that are obliquely oriented along the length of the trachea, may be additionally helpful for radiologist-to-clinician communication. More advanced reformatting techniques such as virtual prospective and retrospective bronchoscopic views (ie, viewing from above and below the injury) and minimum intensity projection reformations can also demonstrate the extent of the injury to the clinician (Fig 4). However, these images tend to

a.



b.

Figure 5. Acute clinically suspected extensive subcutaneous emphysema after elective intubation for scheduled unrelated surgery. **(a)** Coronal radiograph helps confirm massive subcutaneous emphysema and pneumomediastinum extending into the neck bilaterally. **(b)** Axial CT image obtained a few minutes after **a** helps confirm the presence of bilateral pneumothoraces but does not depict the precise site of airway injury. Direct airway injury after elective intubation is rare, and defects may be small and difficult to identify. The use of positive pressure ventilation can lead to rapid respiratory compromise because of pneumothoraces, as in this patient.

be more time-consuming to acquire and are more commonly obtained ad hoc after emergent treatment or before a potentially complex bronchoscopic intervention.

Mechanism of Injury

Most traumatic tracheobronchial injuries can be broadly categorized by mechanism into one of the following types: penetrating, iatrogenic, or blunt force. Nontraumatic caustic inhalational injuries—which can affect the entirety of the tracheobronchial tree—are an important further class of injury but are beyond the scope of this article. Knowledge of the trauma mechanism can aid the radiologist in identifying different typical injury patterns and characteristic complications, which may have particular implications for management.

Varying traumatic mechanisms tend to manifest in different typical sites of tracheobronchial injury. With the exception of gunshot wounds, which can appear in any anatomic distribution, penetrating injuries such as stabbings are more commonly found in the anterior cervical trachea because of its relatively exposed position. Iatrogenic injuries such as those related to bronchoscopic procedures most commonly affect the cervical and proximal intrathoracic trachea, especially the less protected posterior membrane. High-impact blunt force injuries tend to involve the intrathoracic distal trachea near the carina, with a slight preponderance of right-sided involvement.

Penetrating Injuries

Penetrating tracheobronchial injuries most commonly result from stabbing or gunshot injuries. Many penetrating injuries seen by radiologists involve the anterior cervical trachea and mostly occur in instances of stabbing. This may be caused at least in part by higher death rates before hospital arrival in patients with penetrating mediastinal injuries, which may be seen in combination with lethal cardiac or vascular injuries (8,9).

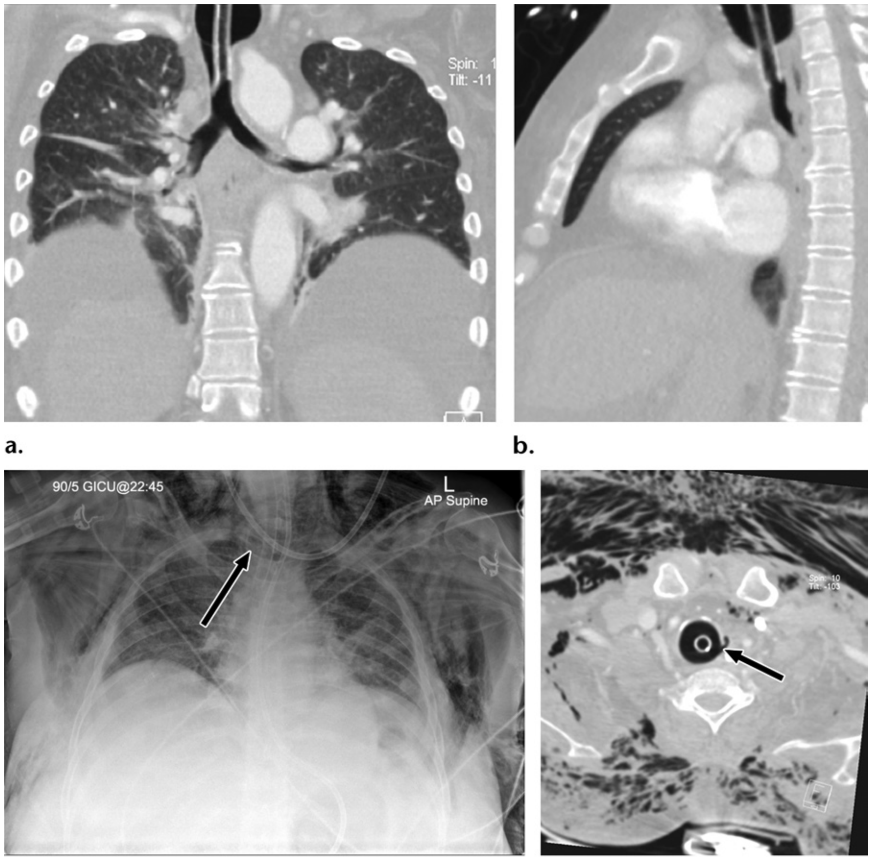
Radiologists should carefully assess images for coexistent esophageal injuries, particularly where there is an apparent full-thickness tracheobronchial injury. Concomitant esophageal injuries and penetrating injuries predispose this group of patients to a high risk of contamination and infection.

Iatrogenic Injuries

Many invasive airway and thoracic procedures can be complicated by iatrogenic tracheobronchial injuries, including endotracheal intubation, bronchoscopy, stent placement, and mediastinoscopy. Head and neck and esophageal surgical procedures may also result in iatrogenic tracheal injuries, with risk factors including previous malignancy, chemoradiation therapy, and extensive nodal dissection (10,11). Overall, the incidence of iatrogenic injury remains low but varies according to the procedure undertaken.

Tracheobronchial laceration or rupture secondary to single-lumen endotracheal intubation—the most common invasive airway procedure—is rare. Its prevalence is challenging to estimate but has been quoted as affecting approximately one in 20 000 to one in 75 000 intubations (12,13) (Fig 5). Although it is rare, intubation-related tracheal rupture is associated with high mortality.

A meta-analysis by Miñambres et al (13) included a total of 182 postintubation tracheal ruptures, in which there were 40 deaths (22%). Emergency intubations and increasing patient age were significantly associated with increased mortality (13).



a. b. c. d.

Figure 6. Endotracheal tube cuff overinflation with delayed tracheal rupture that was missed clinically and on images. **(a, b)** Coronal **(a)** and sagittal **(b)** lung window CT images show a discrepancy of cuff diameter relative to the adjacent trachea, indicating cuff overinflation, which can cause mucosal necrosis. **(c)** Coronal radiograph obtained 2 days later shows the overinflated cuff (arrow), now with extensive subcutaneous emphysema. **(d)** Axial CT image helps confirm that the subcutaneous emphysema is secondary to tracheal rupture (arrow).

Intubation-related tracheal lacerations can cause significant pneumothorax or pneumomediastinum. If a patient undergoes imaging while intubated, extraluminal placement of the tube implicating the site of injury may be depicted. (4,14). Otherwise, the direct site of injury may or may not be visible as a tracheal wall defect or deformity, which is usually present in the posterior membrane of the proximal intrathoracic trachea in a craniocaudal direction.

Rarely, intubation-related lacerations may manifest clinically and appear at imaging after extubation because the cuff may temporarily form a seal at the site of the injury (15). This necessitates a high index of suspicion in the context of respiratory deterioration after extubation and a low threshold to perform CT.

Endotracheal intubation usually causes cuff-related injuries rather than direct lacerations. Cuff overinflation can be depicted at CT or radiography by a discrepancy in cuff diameter relative to the adjacent trachea (Fig 6).

It is rare for overinflation to cause direct tracheal rupture. Indeed, a study using cadaveric tracheas indicated that endotracheal cuffs required high pressures to directly cause tracheal rupture. Tracheal rupture was documented at a cuff air volume of 70–80 mL. This is significantly greater than the recommended volume of 10 mL in the selected endotracheal tube. It is also greater than 50 mL, which was the volume that showed a marked increase in resistance to hand injecting (4).

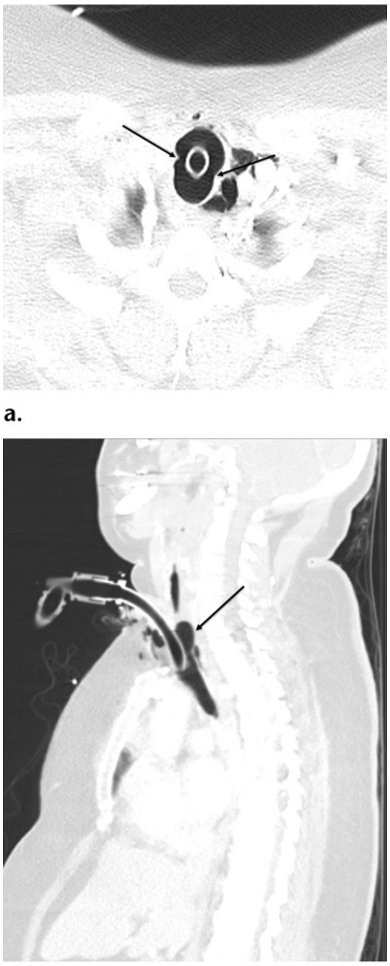
However, cuff overinflation can cause pressure necrosis in the tracheal mucosa, especially in the anterolateral wall, which is less compliant than the posterior membrane because of the overlying cartilage. This can result in delayed tracheal rupture and can manifest as tracheal stricturing because of healing fibrosis in the longer term (Fig 7).

Awareness of the risks of pressure necrosis has led to several clinical preventive adaptations now in common practice, including monitoring of tube cuff pressure. Optimal pressure is generally considered to be below 25 cm H_2O, but this varies according to ventilation and aspiration risk variables (16). It is also now standard to use high-volume, low-pressure cuffs, the mucosal damage from which is more superficial than that associated with low-volume, high-pressure cuffs (16).

Radiologists can also play an important role in depiction of tracheal injury after tracheostomy procedures. Typically, CT may demonstrate a local small volume of subcutaneous emphysema, which usually resolves after a few days and requires no treatment. Occasionally, tracheostomy can be complicated by a stylet introducer injury to the

a. b. c.

Figure 7. Tracheal stenosis. This is a longer-term complication of tracheobronchial injury and is related to endotracheal tube cuff overinflation in the subglottic trachea. **(a)** Axial lung window CT image demonstrates tracheal narrowing (arrow). **(b, c)** Coronal oblique reformations obtained in plane with the tracheal length **(b)** and with minimum intensity projection reconstruction **(c)** more helpfully demonstrate the extent and severity of the stenosis (arrow).



a. b.

Figure 8. Iatrogenic tracheal perforation secondary to tracheostomy introducer stylet. Axial **(a)** and sagittal **(b)** lung window CT images demonstrate herniation of the tracheostomy cuff through the posterior tracheal defect (arrow in **b**), which appears as an hourglass configuration on axial images (arrows in **a**). Defects large enough to cause such an appearance usually warrant surgical repair.

posterior membrane, which usually requires CT for characterization. An hourglass configuration of the tracheostomy cuff as it herniates through the posterior membrane defect can help confirm tracheal injury at imaging (Fig 8). A defect large enough to cause this appearance usually requires surgical repair.

As an increasing number of bronchoscopic procedures are performed, radiologists may encounter their complications more frequently. Tracheobronchial laceration is an important risk to consider when using a rigid bronchoscope, which is metallic and may have a beveled tip. Injury is more likely to occur when it is used in combination with a tortuous or curved airway (Fig 9).

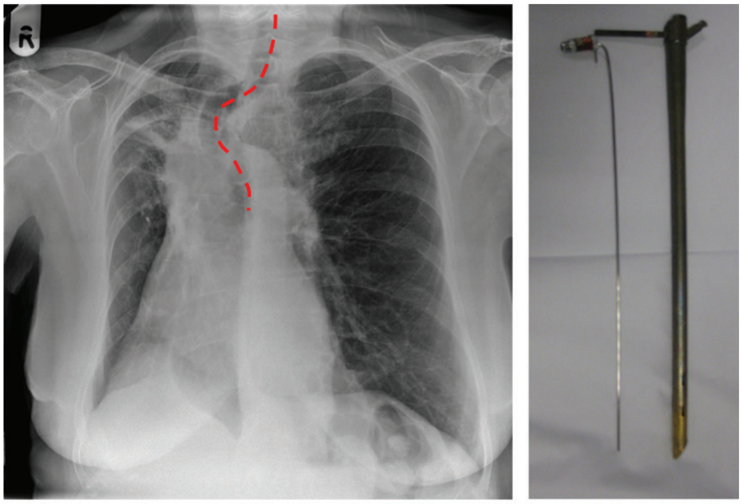
However, in skilled hands, rigid bronchoscopy has low complication rates. Furthermore, it has been successfully used in treatment of tracheobronchial injuries, facilitating application of synthetic adhesives or covered metallic stents (3).

Blunt Force Injuries

Blunt force tracheobronchial injuries usually result from a high-impact mechanism, most commonly in the setting of road traffic accidents. They result from shearing force alone or in combination with increased intrathoracic pressure. Blunt force tracheobronchial injuries occur most frequently in the distal trachea, carina, and proximal main bronchi, more so on the right compared with the left.

In one trauma center retrospective study, CT depiction of blunt tracheobronchial injury correlated well with findings at subsequent bronchoscopy (17). In this study, CT allowed direct visualization of the site of injury in 12 patients, including depictions of a tracheobronchial wall defect, discontinuity, or enlargement and herniation of an endotracheal cuff.

In blunt trauma, careful scrutiny is advised when assessing images of the junction between



a. b.

Figure 9. Tracheal curvature. **(a)** Coronal radiograph shows a right upper lobe tumor with associated collapse and a tortuous trachea (dashed red line). Rigid bronchoscopic right upper lobe stent placement was performed, with ensuing tracheal injury (not shown). **(b)** Rigid bronchoscopes are less suited for use in tortuous airways. Their hard straight properties increase the likelihood of injury during bronchoscopy in a curved airway.

the cartilaginous and membranous portions of the tracheobronchial tree, which is a typical site of vulnerability (17). However, the site of injury is not always directly visualized. In the correct clinical context, there should be a high index of suspicion in the presence of pneumomediastinum adjacent to the main bronchi or distal trachea, even when a site of injury is not definitively identified.

Rare cases that result in complete transection of a main bronchus can appear with the so-called fallen lung sign, originally described by Kumpe et al (18). In this scenario, the lung collapses in the presence of pneumothorax. Instead of collapsing toward the hilum (which would be typical), it drops dependently away from the hilum posteriorly, which may be seen at CT (17,19). If it moves away inferiorly, it may be shown at radiography (Fig 10).

Craniocaudal dependent displacement of the right upper lobe bronchus seen at CT has also been described (19). Although the fallen lung sign remains a widely taught phenomenon and is considered highly specific for tracheobronchial injury, in practice it remains rare. In the literature, it is recognized only in a minority of cases (17,20).

Nishiumi et al (20) performed a clinical-radiologic retrospective review of blunt force tracheobronchial injuries in a single department over 13 years. Of 678 cases of blunt chest trauma, only one of a total of nine cases of tracheobronchial disruption demonstrated complete transection of the left main bronchus with a corresponding fallen lung sign at radiography. Incomplete distal tracheal and proximal bronchial injuries were more common.

The laryngotrachea is a further site of vulnerability in blunt force trauma, including seat belt injuries and hangings, mainly because of the weakness of the cricotracheal membrane. Severe injuries here can manifest with laryngotracheal separation (Fig 11). Imaging findings include discontinuation of the laryngotrachea with deep cervical and prevertebral emphysema, pneumomediastinum, and pneumothorax. A high index of suspicion for laryngotracheal separation should be held when elevation of the hyoid bone is shown, particularly when displaced above the C3 superior endplate, which helps confirm a cricotracheal membrane injury. Associated potentially significant cervical musculoskeletal injuries are common, and thyroid cartilage fractures may also coexist (21).

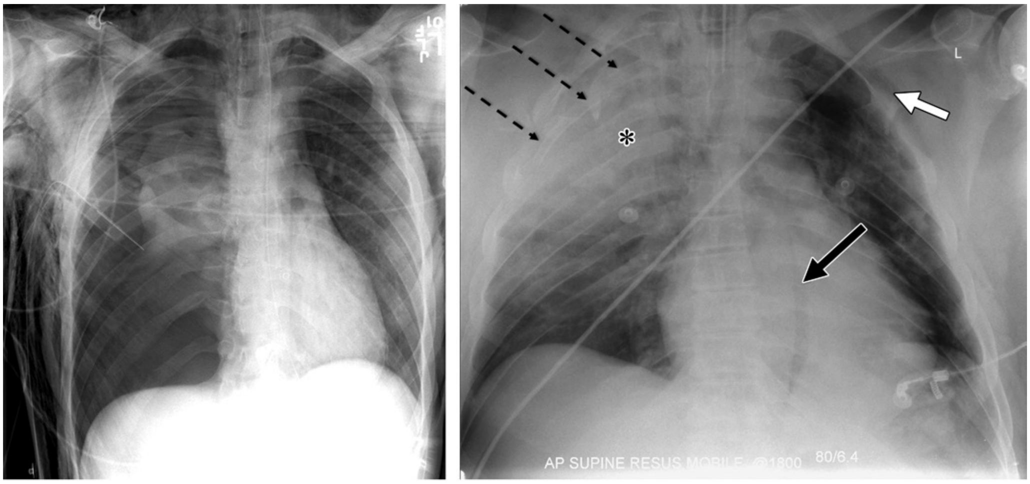
Complications of Tracheobronchial Injuries

Immediate complications from tracheobronchial injuries most commonly result from a persistent air leak in one of several forms. Progressive pneumomediastinum can cause compression on the membranous portions of the trachea and on the bronchi, causing further respiratory compromise and potentially compromising intubation attempts.

Tracheopleural fistulation (Fig 12), which may occur acutely or develop when injuries are left untreated, can be challenging to treat and may progress to a critical condition because of the likelihood of developing tension pneumothorax. Such conditions may be temporized by injecting synthetic adhesives under fiber-optic bronchoscopy (22), but ultimately these patients usually require surgical treatment.

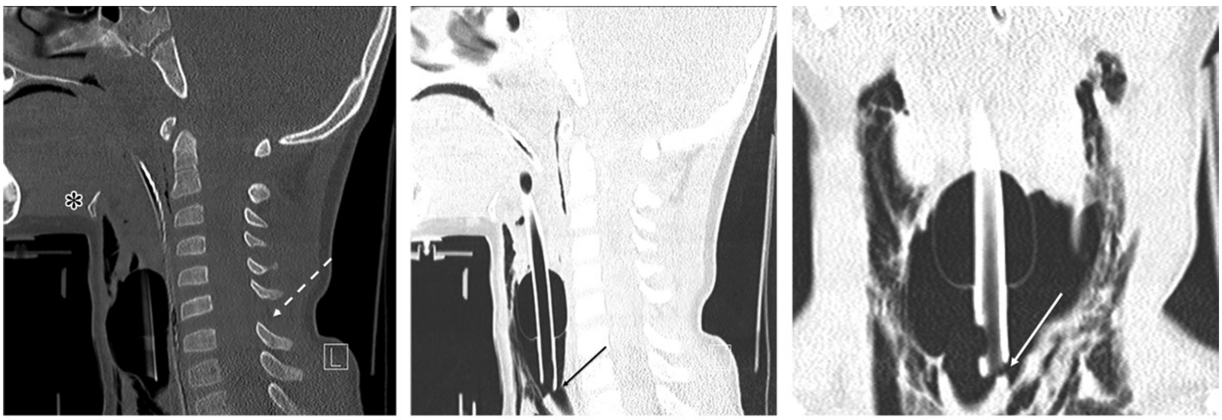
Contamination and infection may complicate tracheobronchial injury in the days and weeks after the injury. It is especially likely in cases of penetrating injury, when there is coexistent esophageal injury, or if positive pressure ventilation is used, which may force secretions into the mediastinum. Indeed, mediastinal sepsis is a common cause of tracheobronchial injury-related deaths and is considered one of the indications for surgical intervention (23).

RadioGraphics



a. b.

Figure 10. Fallen lung sign. This sign is a specific but rare imaging finding in transection of the right or left main bronchus. **(a)** Supine radiograph shows right main bronchus avulsion, extensive pneumomediastinum, and subcutaneous emphysema in an 18-year-old patient after a motor vehicle accident. A large right-sided pneumothorax is present with contralateral shift of the mediastinum despite use of chest drains. The collapsed right lung remains relatively central rather than fallen basally. The trauma supine imaging position may result in a lung falling posteriorly and appearing central rather than inferiorly displaced, as in an erect patient. (Fig 10a courtesy of Sanjeev Bhalla, MD, Mallinckrodt Institute of Radiology, St Louis, Mo.) **(b)** Supine radiograph in a young patient shows a blunt force partial right main bronchus tear. The imaging features are more typical than those in **a** and show parenchymal contusion (*), pneumomediastinum (solid black arrow), subcutaneous emphysema (white arrow), and rib fractures (dashed arrows).



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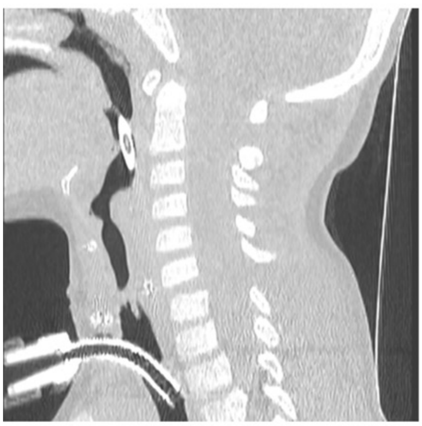
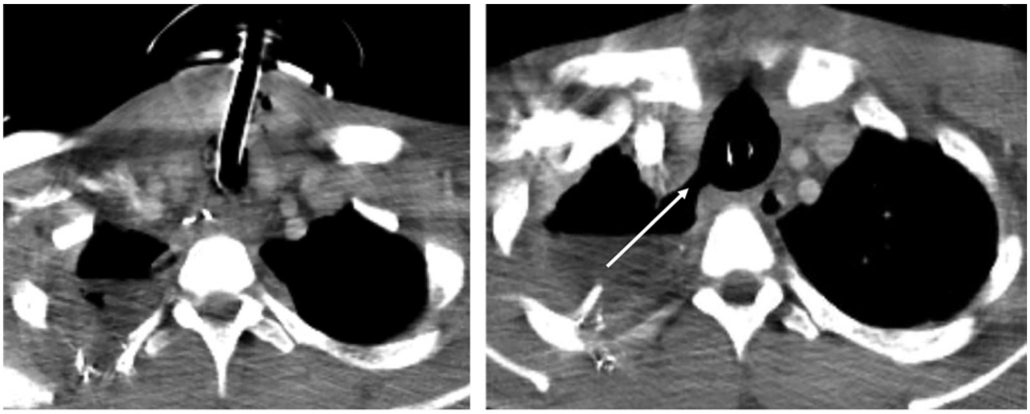


d.

Figure 11. Laryngotracheal injury from a seat belt in a child who was in a road traffic accident involving high-impact blunt force. **(a–c)** Sagittal bone window **(a)** and lung window **(b)** CT reconstructions and coronal lung window CT reconstruction **(c)** obtained on arrival demonstrate elevation of the hyoid bone above C3 (* in **a**), indicating cricotracheal separation. Separation of the larynx from the first tracheal ring (arrow in **b** and **c**) is also shown, with extensive deep soft-tissue emphysema. There is coexistent spinal injury with separation of the C6 and C7 spinous processes (arrow in **a**). **(d)** Ventilation was maintained over the trachea to allow surgical repair above the tracheostomy.

Diagnosis requires an index of clinical suspicion, as several of the CT features of mediastinal sepsis are nonspecific. They may be present in the context of major trauma because of noninfectious causes, particularly hematoma or seroma. CT features that may raise concern for mediastinal sepsis in the correct clinical setting include increased attenuation of mediastinal



a. b.

Figure 12. Tracheopleural fistulation complicating tracheal injury secondary to tracheostomy tube cuff overinflation. Axial soft-tissue window CT images demonstrate a right hydropneumothorax in the presence of a tracheopleural fistula (arrow in **b**) with cuff overinflation. Tracheopleural fistulation can progress to a critical condition if tension develops (not present in this case). (Case courtesy of Myrna Godoy, MD, PhD, MD Anderson Cancer Center, Houston, Tex.)

fat, mediastinal fluid collections, pneumomediastinum, and later, the presence of enlarged mediastinal lymph nodes (24).

More general features of sepsis may be seen. For example, there may be progressive pulmonary infiltrates or the presence of empyema with or without communication to mediastinal collections. In some patients, mediastinal sepsis after sternotomy may cause wound dehiscence (24).

Stricturing is generally a longer-term complication of tracheobronchial injury. Classically, it may arise at a site of prior endotracheal tube cuff overinflation in the subglottic trachea, but it can also complicate direct traumatic lacerations. It is usually the consequence of a granulation tissue healing response, which may occur after mucosal ischemia and necrosis in the case of endotracheal cuff overinflation (25).

Stricturing and subsequent distal atelectasis or collapse seen at imaging months or years after the initial injury may retrospectively unmask previously subtle or occult tracheobronchial injuries, especially those that arise more peripherally and are often less conspicuous (Fig 13).

Multiplanar reformations oblique to the longitudinal axis of the trachea or bronchi or minimum intensity projection reformations can aid in stenosis detection and assessment of severity and length, which in turn can help inform treatment decision making. Treatment options range from conservative management to stent placement or surgical excision (26).

Influence of Imaging Findings on Management

The decision to treat tracheobronchial injuries surgically or nonsurgically will not depend solely on radiologic characterization of the extent and position of the injury. Other factors must be taken into account, including patient comorbidities, local resources and expertise, and (where relevant) the ability to transfer to specialist units. Nonetheless, a description of the imaging features of tracheobronchial injury and other significant injuries can significantly influence treatment decisions.

Notwithstanding the considerations mentioned earlier, certain injuries require surgical repair because of their extent. Surgery is usually performed in lacerations greater than 2–4 cm, especially when there is involvement of the cartilage (Fig 14). Surgery may also be performed in patients with worsening pneumomediastinum, subcutaneous emphysema, or pneumothorax or with a lung that fails to re-expand despite drain placement (15).

Mediastinal sepsis and proximity of the injury to the carina have also been proposed as indications for surgery (23). Emergency surgery is required where there is failure to ventilate or if there is esophageal herniation through the tracheal defect, which may be visualized at CT. Furthermore, if a tracheobronchial injury is identified intraoperatively, then it is usually considered best practice to treat surgically at the time (15,23).

The surgical approach will depend primarily on the location of the tracheobronchial injury, as well as on individual surgical preference. The proximal two-thirds of the trachea can often be repaired with a cervicotomy by using a low cervical collar incision, which additionally provides good exposure to examine vascular structures and the esophagus.

The middle third of the trachea may alternatively be accessed by splitting the manubrium by using a T incision, which also allows assessment of concomitant vascular injury (15). Left main bronchial injuries are usually accessed with a

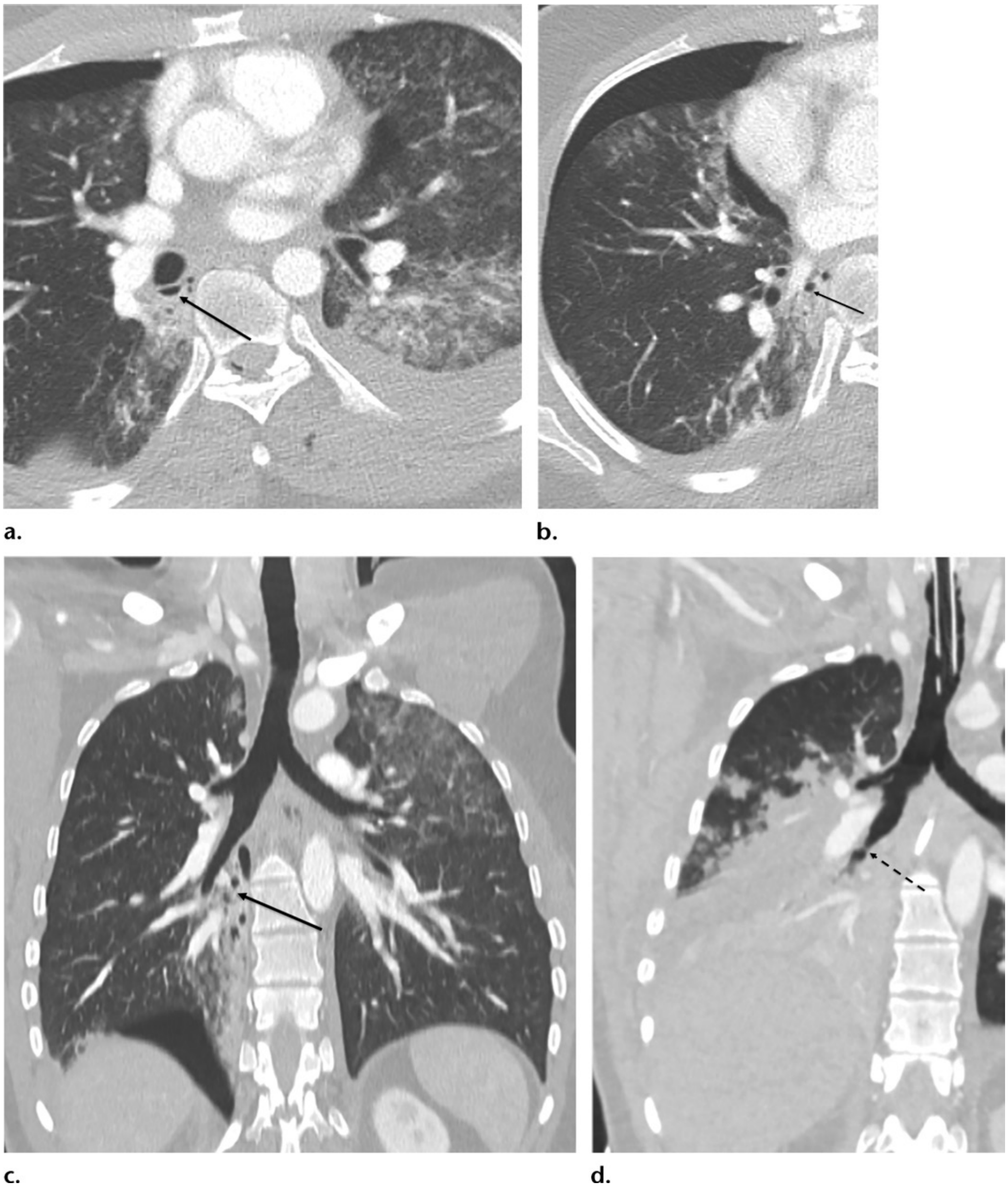
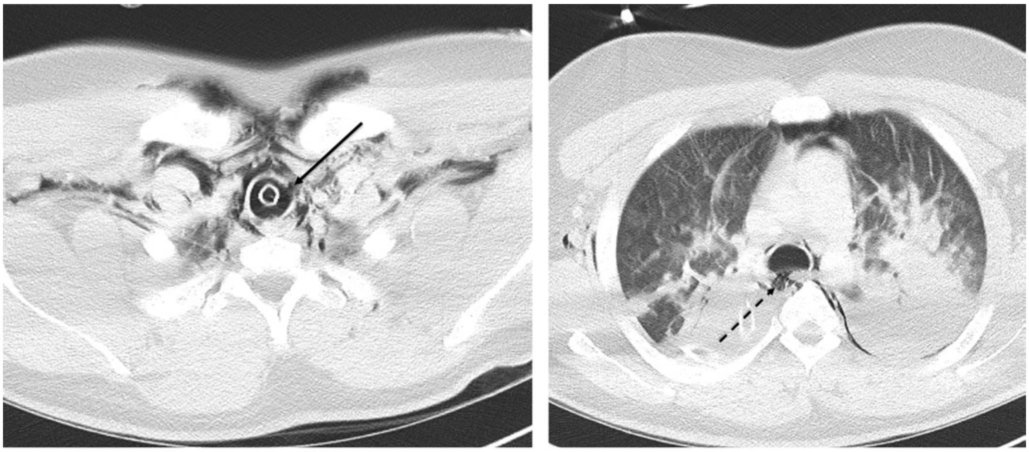


Figure 13. Peripheral bronchial injuries in a cyclist with blunt force trauma. These injuries are easily missed on images because their appearance is often subtle. **(a–c)** Axial **(a, b)** and coronal **(c)** lung window CT images demonstrate right lower lobe bronchial injury, which was initially missed. Small loculi of adjacent extraluminal gas (arrow in **a–c**) are also shown, which were interpreted as pulmonary laceration at the time. Fiber-optic bronchoscopy was not performed. **(d)** Coronal CT image obtained at 2-month follow-up reveals bronchial stenosis (arrow) with postobstructive consolidation.

left thoracotomy, whereas the lower third of the trachea, the carina, and the right main bronchus may all be accessible with a right thoracotomy (15,23). It is rare for sternotomies to be performed because the airway is more difficult to access with this approach.

However, penetrating injuries may require bilateral thoracosternotomy, which is commonly known as a clamshell incision (15). Generally, the superior margins of the main bronchi are easier to visualize and repair at surgery, while the inferior margins are much more challenging. Interestingly, if a patient has a typical 15 tracheal rings, it is generally possible for the surgeon to resect three to four of them without having to mobilize the trachea for anastomosis.

In more borderline cases with lacerations measuring 1.5–2 cm or less, there is increasing momentum behind nonsurgical management options. These include rigid and flexible bronchoscopic application of synthetic adhesives (fibrin- or cyanoacrylate-based), which may be considered in injuries smaller than 5 mm (3, 22), and covered metallic or silicone stent placement, both of which have shown promising results in specialist units (3, 14).



a. b.

Figure 14. Complex tracheal penetrating injury in a patient who underwent surgery after being stabbed with a knife several times. **(a)** Axial CT image (lung window) at the level of the cervical inlet demonstrates extensive pneumomediastinum and subcutaneous emphysema, which are imaging features suggestive of an airway injury. An endotracheal tube is present centrally with a left anterolateral cartilaginous tear (arrow). **(b)** Another injury is shown more inferiorly in the posterior membrane of the trachea (arrow). The depiction of this injury highlights the importance of careful scrutiny of the entire airway on images, since it was thought to be a single through-and-through injury. Extensive parenchymal bilateral dependent consolidation likely reflects hemorrhage and aspiration. Complex injuries involving the cartilage necessitate surgical repair.

Such nonsurgical techniques have also been advocated for patients who are considered high-risk surgical candidates and would otherwise undergo surgery (15). Several advantages of self-expandable metallic stents over silicone stents have been described by Grewal et al (15). When using self-expandable metallic stents, there is an increased likelihood of granulation across the site of injury, which aids healing. They are also superior at contouring to the tracheal or bronchial wall. In addition, metallic stents can be removed after 4–6 weeks. This reduces the complications associated with longer-term placement, such as infection or migration (15).

However, silicone stents offer different advantages, including the ability to be fenestrated to allow passage of tracheostomy tubes. This technique is not possible with use of metallic stents (14).

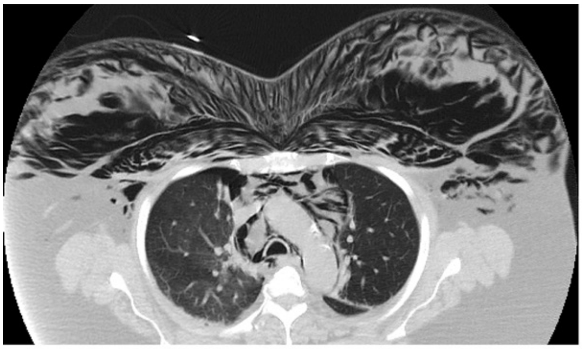
Treatment decisions are frequently made on the basis of imaging findings at CT and the results of bronchoscopic evaluation. Cardillo et al (27) created a grading system for tracheal injuries based on the depth of laceration measured at bronchoscopic assessment. It is frequently used to help guide treatment decisions. The grading system ranges from level I (superficial laceration without mediastinal emphysema or esophageal injury) to levels IIIa (complete laceration with esophageal or mediastinal soft-tissue herniation) and IIIb (any laceration with esophageal injury or mediastinitis) (15,27).

Conservative management is favored for level I injuries, while a surgical approach is usually required for level III injuries. Level II injuries (which extend through the muscle wall with associated pneumomediastinum or subcutaneous emphysema) more commonly require tailored multidisciplinary decision making based on CT findings and the results of clinical assessment of the patient, as described earlier (15,27).

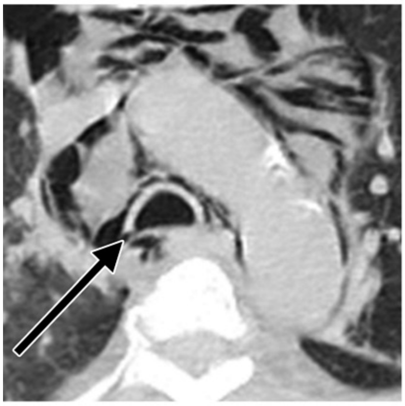
In patients selected for conservative treatment because of limited injury extent or a contraindication to surgery, appropriate positioning of any necessary endotracheal tubes is crucial. Ideally, the cuff should be advanced distal to the site of injury under flexible bronchoscopic guidance (15,23,27), allowing the injury to heal proximally. A chest drain should be inserted where appropriate.

Inadvertent inflation of the cuff at the site of injury may exacerbate the injury through undue pressure (Fig 15). This may be apparent as herniation of the cuff through the airway defect. Therefore, it is important to be attuned to these considerations when assessing endotracheal tube placement at imaging. One should also be cognizant of intentional selective bronchial intubation in cases of left or right main bronchial injuries.

Special consideration is required for patients who require positive pressure ventilation for other reasons. A partial tear of the trachea will likely be stable under self-ventilation but can progress to a critical condition in positive pressure ventilation because of progressive pneumomediastinum or tension pneumothorax (28). Wherever possible, self-ventilation is usually optimal in the setting of tracheobronchial injury. However, in selected cases, positive end-expiratory pressure with low



a.



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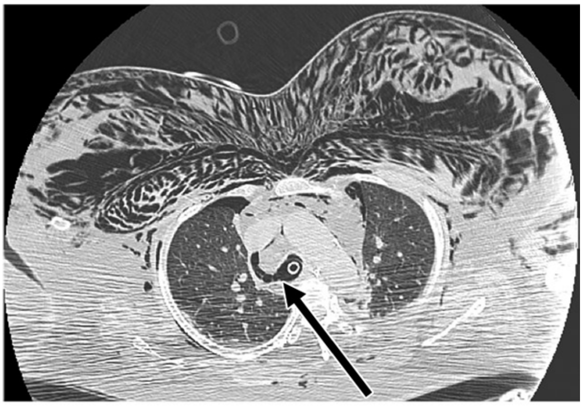

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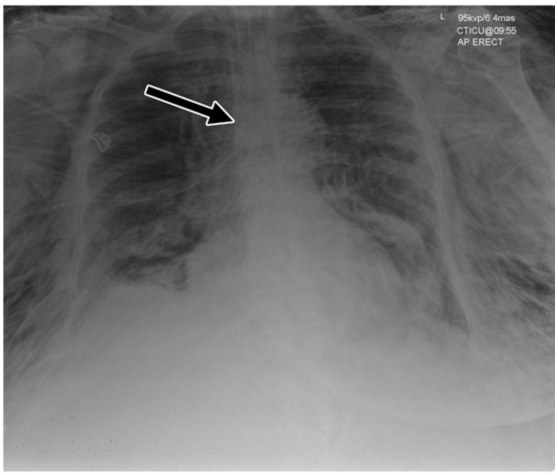

e.

Figure 15. Incorrectly placed endotracheal tube cuff exacerbating tracheal injury in a 70-year-old man involved in a motor vehicle collision. **(a)** Initial CT image obtained at an outside hospital demonstrates extensive anterior chest wall emphysema and anterior and right paramediastinal–predominant pneumomediastinum, which is concerning for an airway injury. **(b)** Axial magnified view of CT image at the same level demonstrates right posterior separation of the tracheal cartilaginous and membranous junction (arrow), which is a common site of injury. Local expertise was not available for airway trauma repair. Selective right main bronchus intubation was performed to maintain ventilation of the right lung, which allowed the patient to be transferred for definitive treatment. The cuff was inflated at the level of the defect. **(c, d)** Axial **(c)** and coronal **(d)** CT images acquired after the patient's transfer show an enlarged defect (arrow in **c**) with development of a small right pneumothorax. Ideal positioning of the endotracheal cuff is distal to the site of injury in most instances. The patient was not considered a surgical candidate. **(e)** Coronal radiograph shows a tracheobronchial covered stent (arrow), which was placed instead of performing surgery. This was unsuccessful. Pneumomediastinum and subcutaneous emphysema worsened, and the patient died a few days later of respiratory failure and sepsis.

tidal volume ventilation distal to the site of injury has shown good outcomes (29).

Conclusion

Although they are rare, tracheobronchial injuries are potentially serious injuries. In the acute setting and at follow-up, imaging plays a critical role in depicting the nature of an injury, its complications, and any associated injury or comorbidity. Knowledge of typical patterns of injury can help the radiologist detect often subtle sites of tracheobronchial defects. In combination with knowing appropriate surgical and nonsurgical treatment options, the radiologist can play a positive role in ensuring the best possible outcomes for this patient cohort.

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