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Review

Imaging of laryngeal trauma

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ABSTRACT

External laryngeal trauma is a rare but potentially life-threatening situation in the acutely injured patient. Trauma mechanism and magnitude, maximum focus of the applied force, and patient related factors, such as age and ossification of the laryngeal cartilages influence the spectrum of observed injuries. Their correct diagnosis and prompt management are paramount in order to avoid patient death or long-term impairment of breathing, swallowing and speaking. The current review provides a comprehensive approach to the radiologic interpretation of imaging studies performed in patients with suspected laryngeal injury. It describes the key anatomic structures that are relevant in laryngeal trauma and discusses the clinical role of multidetector computed tomography (MDCT) and magnetic resonance imaging (MRI) in the acute emergency situation. The added value of two-dimensional multiplanar reconstructions (2D MPR), three-dimensional volume rendering (3D VR) and virtual endoscopy (VE) for the non-invasive evaluation of laryngeal injuries and for treatment planning is discussed. The clinical presentation, biomechanics of injury, diagnostic pitfalls and pearls, common and uncommon findings are reviewed with emphasis of fracture patterns, involvement of laryngeal joints, intra- and extralaryngeal soft tissue injuries, and complications seen in the acute emergency situation. The radiologic appearance of common and less common long-term sequelae, as well as treatment options are equally addressed.

1. Introduction

External laryngeal trauma – blunt or penetrating – is a potentially life-threatening situation in the acutely injured patient and may also result in catastrophic long-term functional sequelae. It is rare with an estimated incidence varying between 1:5000 and 1:137,000 trauma patients [1–6]. However, recent data suggest that its incidence may be higher than previously reported and fractures of the laryngeal skeleton may be diagnosed in almost 1% of all neck trauma patients imaged with multidetector computed tomography (MDCT) in the emergency setting [7]. Depending on trauma mechanism and severity, a variety of injuries have been reported [3,8–10]. Their correct diagnosis and prompt management are paramount in order to avoid patient death or long-term impairment of breathing, swallowing and speaking [2,6]. The mortality of laryngeal trauma is directly related to the capacity to maintain the airways patent while protecting the cervical spine; it may be as high as 80% pre-hospitalization [11]. Nevertheless, once the airways are secured and the laryngeal injury is correctly assessed, the mortality rate decreases to less than 5% [5].

Patients with suspected laryngeal trauma are evaluated clinically, endoscopically and with imaging – mainly CT – to confirm the clinically suspected lesion and to precisely assess its extent prior to treatment [1–7]. MDCT plays a major role for the diagnosis, management and therapeutic choice [12–14], whereas magnetic resonance imaging (MRI) is used as a second line approach. Due to the rapid acquisition of CT data sets with high anatomic detail and the possibility to perform two-dimensional multiplanar reconstructions (2D MPR), three-dimensional volume rendering (3D VR) and virtual endoscopy (VE), non-invasive evaluation and treatment planning are facilitated [7]. Although management of laryngeal trauma has received some attention in the literature, only very few articles have so far dealt with the role of imaging for the work-up of these rare injuries [3,8,15,16]. The purpose of the current review is to provide a comprehensive approach to the radiologic interpretation of imaging studies performed in patients with suspected laryngeal injury. The clinical presentation, mechanism of injury, pitfalls, common and uncommon findings are discussed

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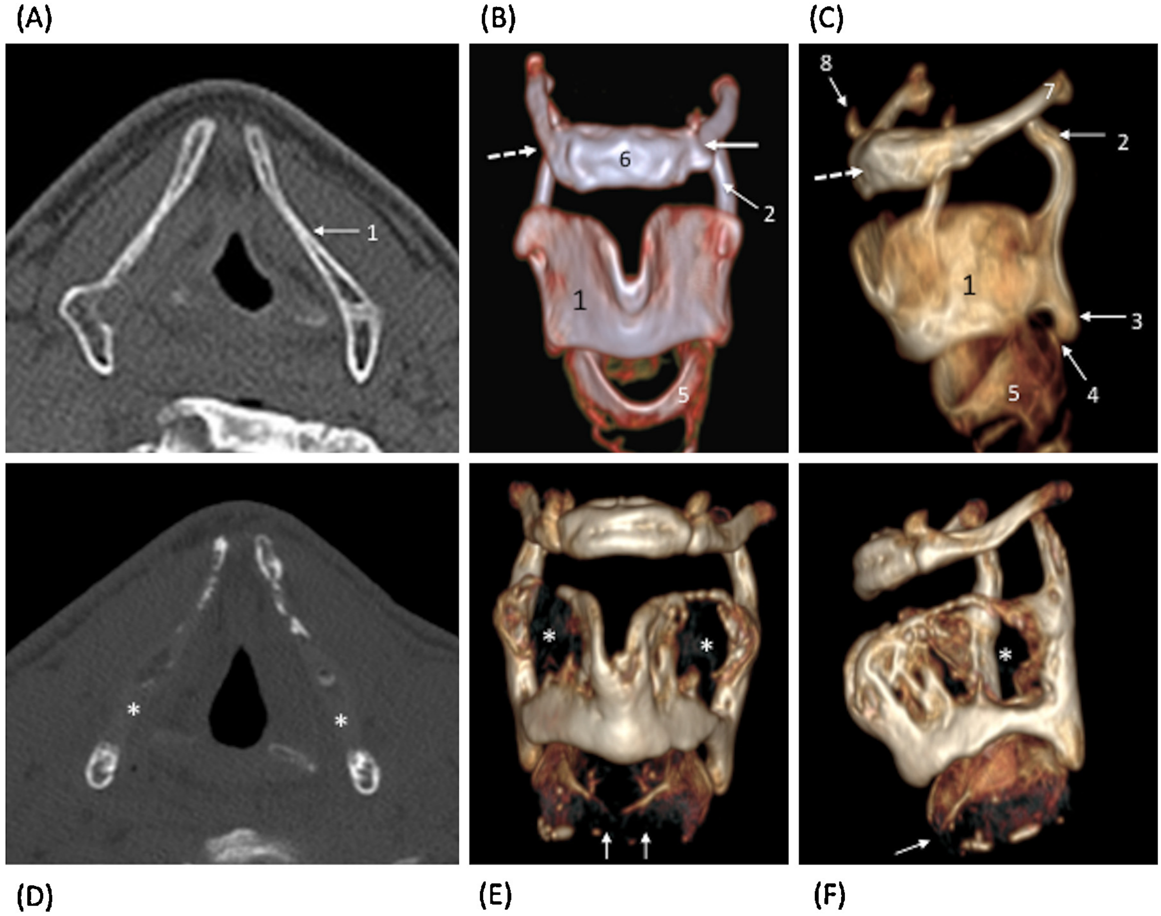

Fig. 1. Normal ossification patterns of the laryngeal cartilages and hyoid bone in a 65 year old male with complete ossification of the thyroid and cricoid cartilages (A–C) and in a 41 year old male with incomplete ossification (D–F). (A and D) Axial images. (B and E) Anterior 3D VR views. (C and F) Right lateral oblique 3D VR views. (1) thyroid lamina; (2) superior horn of the thyroid cartilage; (3) inferior horn; (4) crico-thyroid joint; (5) cricoid cartilage; (6) body of the hyoid bone; (7) greater horn of the hyoid bone; (8) lesser horn of the hyoid bone. Solid arrow in B points at the visible joint between the body and the greater horn of the hyoid bone on the left. Dashed arrows in B and C point at the joint synostosis on the right. Bilateral radiolucent areas within both thyroid laminae in the younger patient (asterisks in D–F) and "missing" anterior cricoid (arrows in E and F) due to incomplete ossification. No present synostosis between the body and greater horns of the hyoid bone in the younger patient.

with emphasis on fracture patterns, intra- and extralaryngeal soft tissue injuries and complications seen in the acute emergency setting. The radiologic appearance of long-term sequelae is equally reviewed. The review focuses on the respective role of MDCT and MRI for the assessment of laryngeal trauma.

2. Relevant anatomy and pitfalls related to ossification patterns of laryngeal cartilages

Although a detailed description of laryngeal anatomy is beyond the scope of this article, knowledge of the relevant anatomy is essential for the understanding of trauma mechanisms and their effects on laryngeal structures. The laryngeal skeleton comprises three unpaired cartilages (thyroid, cricoid and epiglottis) and three smaller paired cartilages (arytenoid, cuneiform and corniculate cartilages), all connected by membranes, ligaments and muscles. The thyroid cartilage has two laminae joined together anteriorly. Posteriorly, the laminae form a superior and an inferior horn. Superiorly, the thyroid cartilage is attached to the hyoid bone via the infrahyoid muscles and the thyrohyoid membrane. Inferiorly, it is attached to the sternum and to the cricoid cartilage with which it forms the crico-thyroid joints (Fig. 1).

The epiglottis, the vocal process of the arytenoids, the cuneiform and corniculate cartilages are composed of elastic fibrocartilage and do not ossify. The remaining cartilages, however, are composed of hyaline cartilage and undergo ossification as part of the normal aging process [17–20]. In general, the degree of ossification of the thyroid and cricoid cartilages is lower in females as compared to males [20]. The thyroid cartilage begins to ossify in both sexes at the posterior inferior border and in the inferior horns around the age of 18–20 years [18]. Ossification then involves the superior horns and the superior border of the thyroid laminae. Although by the age of 65, the thyroid cartilage may be completely ossified (Fig. 1), the central portions of the thyroid laminae may remain non-ossified throughout life appearing as radiolucent areas on conventional X rays [19] and on 3D VR (Fig. 1). Although a single bilateral radiolucent area is observed in most cases on 3D VR, occasionally, two such areas may be seen. 3D VR may also show inward bending of the superior horns as a normal variant (Fig. 2); this variant should not be confounded with greenstick fractures of the superior horns.

The cricoid cartilage has the form of a signet ring with a broader lamina located posteriorly. The crico-thyroid membrane attaches the cricoid cartilage superiorly to the thyroid cartilage while the crico-tracheal ligament fixes the cricoid cartilage inferiorly to the first tracheal ring. Ossification of the cricoid cartilage first involves the superior cricoid lamina, after which the remainder of the signet portion ossifies. The cricoid cartilage is less well ossified than the thyroid cartilage; therefore, it is less well seen on 3D VR, its anterior portion often appearing as "missing" on 3D VR reconstructions (Fig. 1).

The arytenoid cartilages have a pyramidal shape. The base of each arytenoid cartilage articulates with the posterior cricoid

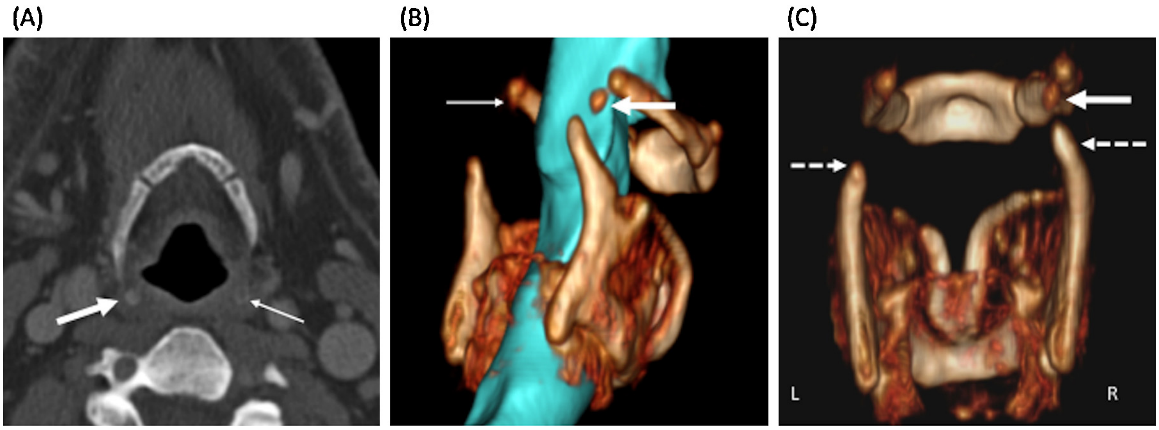

Fig. 2. Diagnostic pitfall: asymmetric ossification of the tritiate cartilages and inward bending of the superior thyroid horns. (A) Axial image through the hyoid bone and the tritiate cartilages. The right cartilago triticea (thick arrow) is easily seen due to its increased ossification whereas the left cartilago triticea can hardly be distinguished (thin arrow). (B) Right posterior 3D VR view. Cartilages and hyoid bone are illustrated in brown, the airway in blue. The right tritiate cartilage (thick arrow) is easily seen, whereas the left tritiate cartilage (thin arrow) appears to be missing due to its poor ossification. (C) Posterior 3D VR view. R = right. L = left. Arrow points at the right tritiate cartilage. Dashed arrows point at the superior horns of the thyroid cartilage. Note their inward bending especially on the right.

lamina forming the crico-arytenoid joint. Each arytenoid cartilage has an anterior vocal process and a lateral muscular process. The vocal ligament is attached to the vocal process while the lateral and posterior cricoarytenoid muscles insert to the muscular process. Ossification of the arytenoid cartilages, as seen on CT, is most often symmetric; however, asymmetric ossification with a dense (sclerotic) aspect unilaterally may occur in up to 13% of normal arytenoid cartilages [21]. On 3D VR, the arytenoid cartilages often have rounded borders, as the vocal process never ossifies and the muscular process and the apex most often do not.

The hyoid bone is anatomically and functionally closely related to the larynx. It consists of a body, two lesser and two greater horns (Fig. 1). Contraction of the suprahyoid musculature results in elevation and anterior movement of the hyoid bone and larynx, whereas contraction of the infrahyoid muscles leads to depression and backward movement of the hyoid bone. The infrahyoid muscles may also either act as elevators of the thyroid cartilage (thyrohyoid muscle) or as depressors (sternothyroid muscle). Injury to the suprahyoid and/or infrahyoid muscles results in abnormal positioning of the hyoid bone with respect to the larynx (see below). Ossification of the hyoid bone starts in the greater horns, continues in the body and proceeds to the lesser horns. Although ossification of hyoid bone is completed before the age of 20, the fibrous connection between the body and the greater horns may persist until late in life (Fig. 1). Ossification of the hyoid bone is typically symmetric and homogenous. However, heterogenous (but symmetric) ossification may be seen in the posterior portion of the greater horns; this variant should not be confounded with fractures.

The paired tritiate cartilages are located halfway between the superior horns of the thyroid cartilage and the greater horns of the hyoid bone. Their variable and asymmetric attenuation values on MDCT (Fig. 2) constitute a diagnostic pitfall and should not be misdiagnosed as avulsed cartilaginous fragments.

Evaluation of the injured larynx also requires careful analysis of the mucosal and submucosal soft tissues as identification of subtle abnormalities within the paraglottic or preepiglottic space may suggest cartilage fracture or avulsion. The bilateral paraglottic space mainly contains fat. At the level of the false cords, fatty tissue surrounds thin bands of muscle. Increased attenuation values or asymmetry of the paraglottic fat should raise the suspicion of hematoma. As the paraglottic space extends into the aryepiglottic folds, hematoma may also extend posteriorly into the hypopharynx. At the glottic level, the thin paraglottic fat is located between the thyroarytenoid muscle medially, and the thyroid and cricoid cartilages, laterally. Absence of visualization of the fatty tissue at this level on MDCT, in particular anteriorly, does not necessarily indicate pathology. The preepiglottic space – located between the epiglottis posteriorly and the thyrohyoid membrane and thyroid cartilage anteriorly – mainly contains fatty tissue. Increased attenuation values and a reticulated aspect suggest hematoma and warrant careful evaluation of the epiglottis (see below).

3. Imaging techniques

The first priority in the emergency situation is to establish a secure airway, which may require orotracheal intubation or tracheostomy prior to any further procedure. Once the airways and the cervical spine are secured and the patient remains stable, CT is indicated in order to determine the presence and extent of damage to the laryngeal framework [1–10,22–24].

3.1. MDCT

MDCT is the examination method of choice to evaluate laryngeal trauma and associated lesions, as it allows rapid scanning and assessment of large anatomic areas with high quality, high-resolution images [9,25–31]. It enables reliable evaluation of dyspneic or ventilated patients in the emergency situation [7,13,32] and in routine imaging. Thin slices (1–1.2 mm reconstructed with 50% overlap) are mandatory, as the detection rate of fractures depends on the slice thickness used. Thin slices with overlapping reconstructions allow 2D MPR, 3D VR and VE reconstructions of good quality. Axial 2D MPR should be strictly perpendicular to and coronal 2D MPR should have a parallel orientation to the airways. 2D MPR need to be corrected for neck tilting or rotation to avoid misinterpretation. Most PACS systems currently allow real-time 2D MPR with multiple rendering modes: average MPR, minimum Intensity Projection (mIP), Maximum Intensity Projection (MIP) and thick slab MPR [33]. 3D VR enable external 3D views of the cartilages and airways, as well as multiple layer reconstructions. Multicolor display of various anatomic structures on a single 3D image warrants more accurate depiction of the spatial relationship of various injuries. VE provides “fly through” images similar to endoscopy thus facilitating interdisciplinary communication.

Evaluation of soft-tissue and bone windows is mandatory. Bone windows are essential to detect subtle fracture lines in ossified cartilages while soft-tissue windows allow improved assessment of non-ossified cartilages and submucosal tissues. There is no consensus today whether intravenous administration of contrast material is indispensable for the assessment of laryngeal trauma. In our hospital, we administer intravenous contrast material to all multi-trauma patients (whole-body multi-trauma MDCT protocol) and whenever vascular injuries are suspected.

3.2. MRI

MRI is infrequently used for the assessment of the traumatized larynx. Nevertheless, in young patients with non-ossified cartilages or in patients with poorly ossified cartilages, MDCT may miss laryngeal fractures and cartilage avulsions [9,34]. Therefore, MRI should be used in those patients in whom laryngeal fractures are suspected clinically and where MDCT findings do not clearly show the laryngeal injury. In our institution, we do not perform MRI as a first line approach in laryngeal trauma but reserve it for the cases with normal or unclear MDCT findings and a strong clinical suspicion of cartilage fracture. In consequence, high-resolution MRI with surface coils is performed within the first 24 h after emergency admission provided that the clinical situation permits it. Due to the length of the MRI examination, particular care should be taken to secure the airways (tracheotomy or intubation) prior to the exam. Patients without airway impairment should be observed or monitored carefully and the duration of the examination should be kept to a minimum to avoid unnecessary risks related to secondary airway compromise due to acute soft tissue swelling. The minimum MRI protocol in the traumatized larynx includes: axial T2w, T1w $\pm$ fat saturation before and after injection of gadolinium chelates. If the clinical situation permits, additional coronal or sagittal T1w and T2w sequences may be acquired. Because the mix between hematoma, soft tissue laceration and edema in the larynx may have similar signal intensity as the laryngeal cartilages on T1w and T2w sequences, in our experience, the administration of gadolinium chelates enables improved differentiation between fractured cartilages with small dislocated fragments and surrounding soft tissues: while the traumatized soft tissues typically show enhancement following contrast administration, the fractured hyaline cartilages remain hypointense. Visualization of fracture lines within non-ossified cartilages is only possible if high-resolution images are obtained. Therefore, the field of view should be small, and the matrix high (512×512). The slice thickness should not exceed 2–3 mm, whenever possible.

4. Trauma mechanisms and clinical presentation

Laryngeal trauma mechanisms can be classified as blunt or penetrating and as external or internal. Internal trauma is often iatrogenic, typically following intubation, or may be rarely caused by sneezing with a closed mouth, so called "closed airway sneeze" [35]. External trauma is seen after motor vehicle and sports accidents, falls, strangulation, stab and gunshot injuries. External laryngeal trauma affects younger males with a reported mean age ranging from 24 to 44 years [2,4,5]. Fractures are either complete or the perichondrium may be preserved (greenstick fractures). Experimental studies have shown that the occurrence of laryngeal fractures depends on the degree of ossification [36]. The increased ossification of laryngeal cartilages in elderly patients seems to predispose to comminuted fractures [37].

4.1. Blunt trauma

The incidence of blunt external laryngeal trauma is difficult to estimate, as it may vary from one trauma center to another. The major cause is a direct anterior impact on the larynx in a motor vehicle accident. Although anterior blunt laryngeal injury due to automobile accidents is in general decreasing (seat belt laws, front seat airbag, lower speed limitation), laryngeal trauma due to two-wheelers seems to be increasing. In a rear-end collision, the passenger and the driver are hit from behind causing neck hyperextension and forward propulsion. The larynx is crushed between the steering wheel, dashboard or the seat belt anteriorly and the rigid cervical spine posteriorly. In low velocity accidents, fractures of the hyoid bone and soft tissue injury are observed. At high velocity, thyroid and cricoid fractures with major soft tissue lacerations are noted. While non-ossified cartilage may spring back after being exposed to an anterior crushing force, ossified cartilage shatters resulting in airway impairment (Fig. 3).

Clothesline injuries typically occur when the rider of a two-wheeler, encounters a fixed horizontal object stretching across his path. Due to the large amount of energy applied to a small area of the neck, the cricoid cartilage is shuttered and crico-tracheal separation may result. As the injured airway is often hidden beneath the intact skin [38] the diagnosis may be missed initially.

Strangulation injuries occur due to compression of the larynx manually, by a soft object or by hanging. Clinically, abrasion of the neck is typically seen. Survivors may develop laryngeal edema 12–24 h later although mucosal lacerations and hematomas may be absent initially. Following strangulation, fractures of the thyroid cartilage and hyoid bone are common with a reported incidence of up to 50% at post-mortem examinations. Other causes of blunt laryngeal trauma include sports related accidents and falls from different heights.

4.2. Penetrating trauma

The incidence of penetrating laryngeal trauma has been increasing during the past years because of the increasing number of personal assaults [22]. Penetrating laryngeal trauma constitutes up to 15% of all penetrating neck injuries [22]. Stab wounds are tricky, as although the skin orifice may appear small upon clinical examination, the greatest damage may be located deep in the neck. The precise wound trajectory is difficult to estimate clinically and possible vascular lesions are difficult to assess unless contrast-enhanced CT is performed (Fig. 4). There is an increased risk of secondary aggravation due to massive hemorrhage, emphysema and soft tissue edema with acute asphyxia.

Gunshot wounds are often complex injuries with shattered laryngeal cartilages, vascular, maxillo-facial and/or cervical spine lesions. The degree of injury depends on the deposited energy, weight and shape of the bullet, as well as the firing range. Typically, the zone of internal injury is much larger than appreciated at initial clinical evaluation. On entering tissue, a bullet creates a temporary pulsatile cavity due to acute tissue distension by the transmitted pressure (100–200 atmospheres). This temporary pulsatile cavity, which has a lifetime of only a few milliseconds, may cause major distant damage due to the resulting shock wave. If the pressure of the temporary cavity exceeds the elastic limit of the laryngeal tissues, the larynx bursts. In addition, the fragments resulting from the shattered laryngeal cartilages or bones may become secondary projectiles, thus increasing wound size. Close-range wounds are often fatal due to the intense energy applied to the larynx, while damage is less important in long-range wounds (Fig. 4).

4.3. Symptoms and clinical findings

Symptoms upon admission may vary considerably and do not always correlate with the degree of internal injury [38]. They include anterior neck pain, dysphonia, dyspnea, stridor, dysphagia, cough and hemoptysis. Clinical findings comprise ecchymosis, hematoma, neck wound, pain and cracking upon palpation [4–6]. In a stable patient, the larynx is evaluated with flexible endoscopy

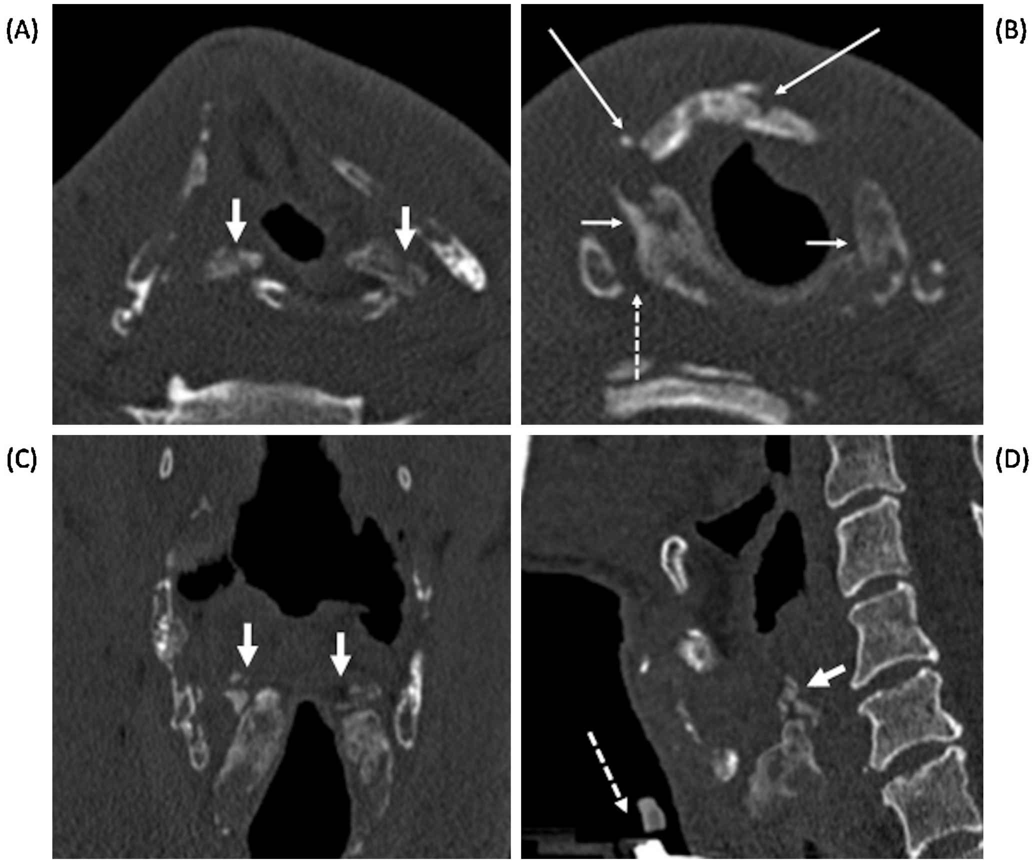

Fig. 3. Major laryngeal trauma with shattered ossified cartilages and acute airway impairment necessitating tracheotomy prior to CT. Axial bone window images at the glottic (A) and subglottic level (B), coronal (C) and sagittal (D) 2D MPR show multiple fractures involving the thyroid cartilage (thin long arrows in B), the cricoid (short thin arrows in B) and the arytenoids (short thick arrows in A, C and D). Widening of the right crico-thyroid distance (dashed arrow in B) suggesting disjunction of the right crico-thyroid joint. Tracheostomy tube (dashed arrow in D).

enabling detection of hematoma, lacerations, edema, impaired vocal cord mobility or arytenoid dislocation. In severe laryngeal trauma, exposed cartilages may be seen protruding into the lumen. Assessment of airway patency is paramount, as it allows evaluation not only of the acute situation, but also potential impairment within the next hours or days.

In some patients, no symptoms suggesting a laryngeal fracture may be present initially and dramatic swelling of the unprotected airway may occur several hours after admission [2,38]. Furthermore, in patients intubated or tracheostomized prior to emergency admission, symptoms cannot be assessed. Therefore, until proven otherwise, injury of the larynx should be suspected in all patients with anterior neck trauma. A high index of suspicion is required making careful assessment of MDCT images in the emergency situation mandatory [7].

5. Classification of laryngeal injury

In an attempt to correlate the type of injury with treatment options, several classifications of laryngeal injury have been used during the past years. The most commonly used classification is the one proposed by Schaefer and Fuhrman [2,39], which takes the severity of injury, initial treatment and outcome into consideration (Table 1). Some injuries, such as mucosal lacerations, are detected more easily with endoscopy. Other injuries, however, such as fractures of the laryngeal cartilages are seen more obviously on MDCT or MRI. Therefore, a combined clinical, endoscopic and radiologic approach is mandatory to classify laryngeal injuries [2,39].

6. Injuries associated with laryngeal trauma

Approximately 50% of all patients with laryngeal trauma have additional injuries involving not only neck structures but also the face, brain, lung, spine, or abdomen [4,5,7,40]. The reported incidence of associated intracranial injury is about 13–15% [5,7]. Skull base and facial fractures may be seen in up to 21% of patients and cervical spine fractures in up to 8% [5,7]. While large soft tissue hematomas may be quite common in all types of laryngeal trauma, arterial and venous vascular lesions, as well as pharyngeal and esophageal lacerations are more common in penetrating injuries [23,24]. From a surgical viewpoint, penetrating neck injuries are

Table 1
Classification scheme for categorizing the severity of laryngeal injuries.

Groups	Severity of injury in ascending order
Group 0	Normal larynx
Group 1	Minor endolaryngeal hematomas or lacerations without detectable fractures. No airway compromise
Group 2	More severe edema, hematoma, minor mucosal disruption without exposed cartilage, or nondisplaced fractures. Varying degrees of airway compromise
Group 3	Massive edema, large mucosal lacerations, exposed cartilage, displaced fractures, or vocal cord immobility. Airway compromise
Group 4	Same as group 3, but more severe, with disruption of anterior larynx, unstable fractures, two or more fractures lines, or severe mucosal injuries. Requires the use of a mold for stabilization
Group 5	Complete laryngotracheal separation

Source: Modified after Schaefer et al. [2] and Fuhrman et al. [39].

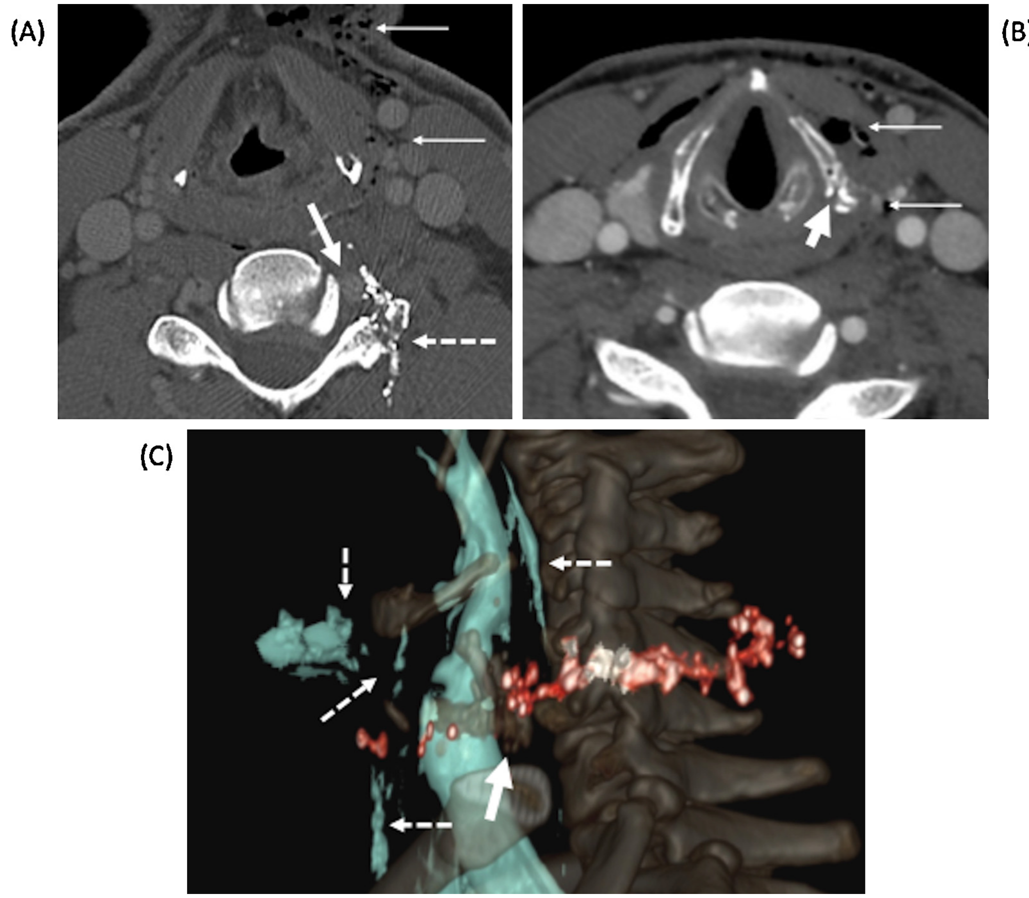

Fig. 4. Long range, zone II gunshot injury with thyroid cartilage fracture. Axial images at the supraglottic (A) and subglottic (B) level show shattered articular process of C5 and thyroid cartilage fracture (short thick arrow in B). Note scattered bony fragments and small metallic foreign bodies (dashed arrow in A) along the bullet trajectory and in immediate vicinity of the vertebral artery (thick arrow in A). There is also soft tissue emphysema along the bullet trajectory (thin long arrows in A and B). C. Multilayer 3D VR of the airways (blue), laryngeal cartilages (brown), bony structures (brown), soft tissue emphysema (dashed arrows) and bullet trajectory (red) showing the position of the thyroid cartilage fracture (thick arrow) with respect to the bullet trajectory. The reconstruction of the bullet trajectory was obtained by applying a separate layer on the 3D VR with a threshold allowing identification of small metallic fragments.

classified according to the three anatomic zones of the neck [24]. Zone I extends from the thoracic inlet to the cricoid cartilage. Zone II is located between the cricoid cartilage and the mandible. Zone III extends from the mandible to the skull base. Zone I is prone to lesions of the cricoid cartilage, subclavian arteries and veins, trachea, esophagus, and intra-thoracic injuries. Zone II is at risk for injury of the glottic and supraglottic larynx, hyoid bone, hypopharynx, carotid and vertebral arteries, while Zone III is at risk of major facial or intra-cranial injuries [24,41]. Most penetrating laryngeal injuries are Zone II lesions (Fig. 4). Nevertheless, it is important to remember that in penetrating neck injuries, the site of the entry wound may be remote from the location of the deep injury, as the wound tract may cross into another zone, the face, chest or skull [32]. Therefore, one should bear in mind wound trajectory on MDCT paying particular attention to possible distant injury sites.

7. Imaging findings in the acute trauma setting

7.1. Laryngeal soft tissue injuries

In moderate severity trauma, hematoma, edema and mucosa lacerations without fractures (Schaefer group 1 lesions, Table 1) are observed. The elastic larynx may absorb the shock; however, as it recovers its shape, the thyroarytenoid muscle or the vocal ligament may tear. Lesions of the vocal ligament and thyroarytenoid muscle should be suspected on MDCT whenever thickening due to hematoma or bulging of the vocal cords into the airway lumen is detected. Although MRI is superior to CT for the assessment of laryngeal hematoma, correlation with endoscopy is mandatory (Fig. 5). Small hematomas tend to be missed at MDCT; diagnosis of larger hematomas, however, is straightforward due to the presence of a lesion with high attenuation values (60–70 HU) on unenhanced images. Laryngeal edema most often causes symmetric soft tissue thickening and airway narrowing on CT while mucosal lacerations are diagnosed whenever air within the paraglottic space [28] with or without interruption of the laryngeal mucosa is seen. Mucosal lacerations are difficult to diagnose on axial CT images alone and 2D MPR, 3D VR and VE are of additional help by revealing irregular, air-filled pouches communicating with the laryngeal lumen.

7.2. Fractures of the laryngeal cartilages

Trauma of increased severity may cause larger hematomas, major edema and lacerations, as well as fractures with or without fragment displacement (Schaefer groups 2 and 3, Table 1). Fractures are diagnosed whenever the continuity of ossified or non-ossified cartilage is interrupted. Associated cartilage deformation is not always present (Fig. 6). In general, the diagnosis of fractures involving ossified cartilages is easier on CT (Fig. 6) than the diagnosis of fractures involving non-ossified portions. In major trauma, fractures are often unstable (Fig. 3) with multiple displaced fragments

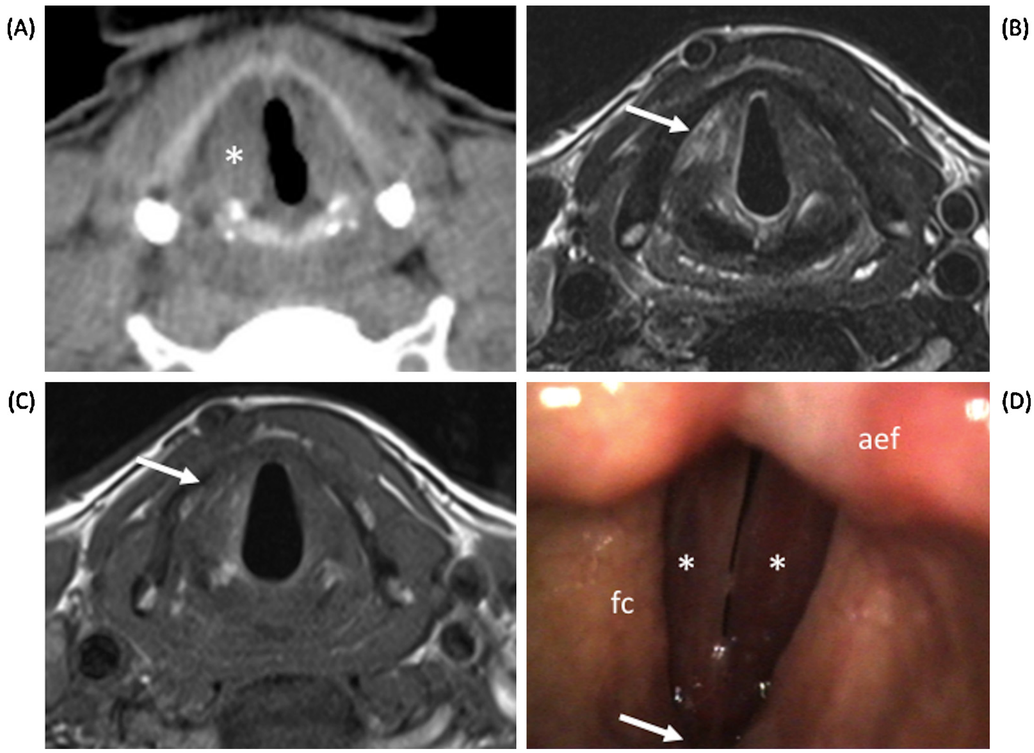

Fig. 5. Glottic hematoma, as seen on MDCT and MRI in the acute trauma setting. Axial CT image at the glottic level (A) shows slight enlargement of the right vocal cord (asterisk) and no obvious difference in attenuation values between both cords. Axial T2w (B) and T1w (C) images obtained at the same level clearly show hematoma involving the right thyroarytenoid muscle and the right paraglottic space (arrows). The hematoma has high signal intensity on both sequences due to the presence of methemoglobin. The left vocal cord looks normal. (D) Flexible endoscopy (view from above during phonation) reveals bilateral hematoma (asterisks) and normal vocal cord mobility. aef, left aryepiglottic fold; fc, right false cord. Arrow points at the normal anterior commissure.

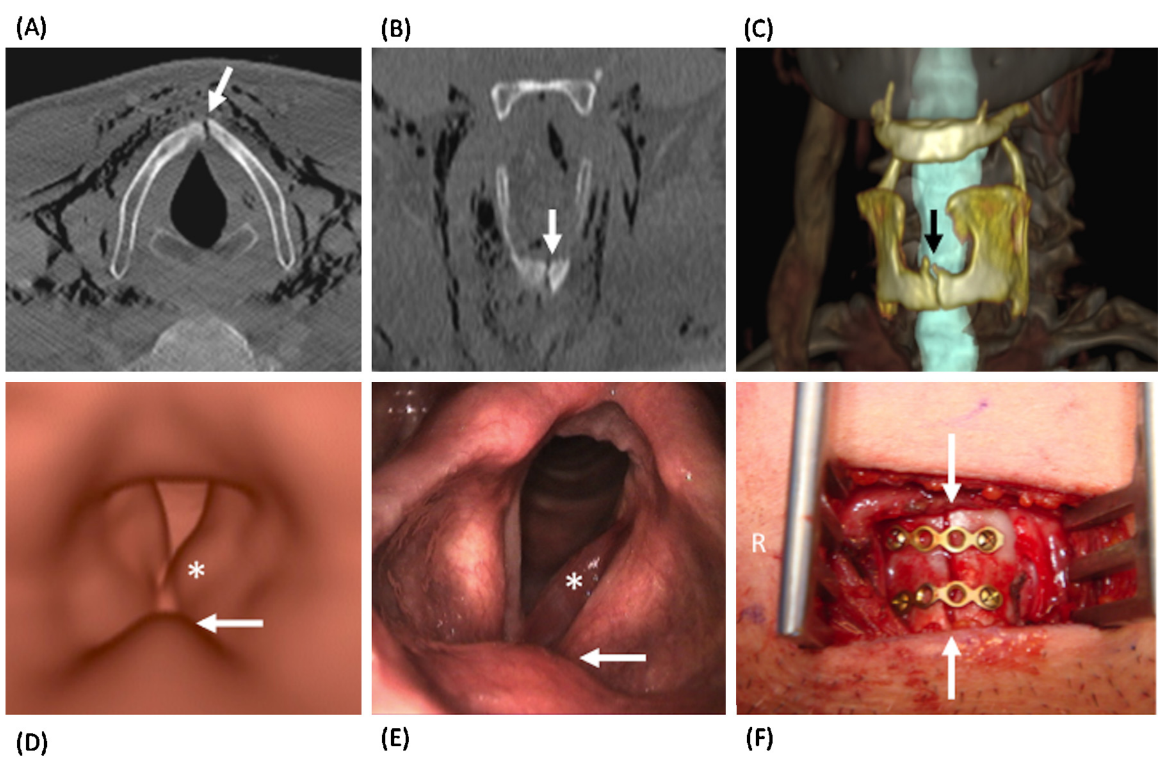

Fig. 6. Isolated longitudinal fracture of the thyroid cartilage due to motor vehicle accident. Axial (A) and coronal (B) 2D MPR with bone windows show a paramedian, longitudinal fracture of the thyroid cartilage (arrows) with major soft tissue emphysema. (C) 3D VR (anterior view) of the thyroid cartilage (yellow) and airways (blue) depicts the cranio-caudal extent of the fracture line (arrow) more precisely. Note that in this young patient, the thyroid cartilage is poorly ossified in its anterior portion. (D) VE image shows slight bulging of the left anterior vocal cord (asterisk) due to localized hematoma and inward bulging of the anterior commissure (arrow) due to the underlying fracture line. (E) Corresponding endoscopic image confirms the VE findings. Hematoma of the anterior left vocal cord (asterisk) and anterior submucosal bulging due to thyroid cartilage fracture (arrow). F. Intraoperative frontal view. R = right side. Surgery confirmed the CT findings. Arrows point at the longitudinal fracture line still visible after cartilage fixation with mini-plates.

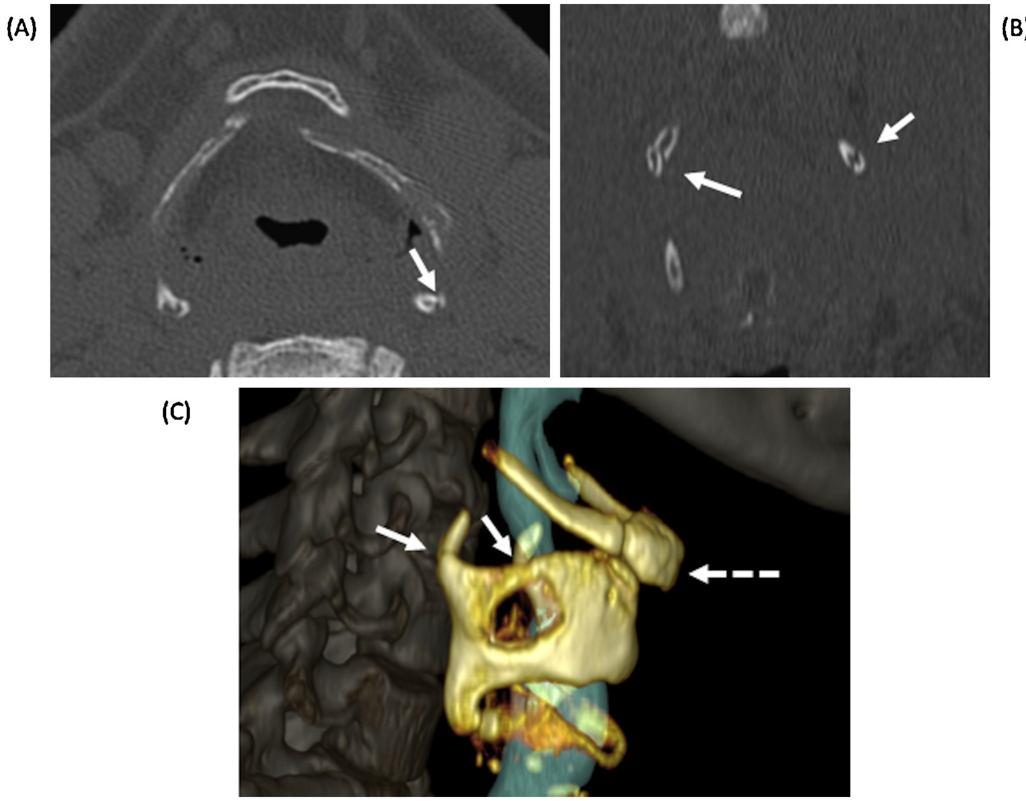

Fig. 7. Horizontal fracture of the thyroid cartilage caused by hanging. Axial (A) and coronal (B) bone window 2D MPR show fractures of the superior horns of the thyroid cartilage (arrows) without associated soft tissue emphysema. Note that in (A) only the left fracture line is seen, whereas in B, involvement of both superior horns is readily appreciated (arrows). Right lateral (C) 3D VR of cartilages and hyoid bone (yellow), and of airways (blue) show an abnormal anterior tilting and inferior displacement of the hyoid bone (dashed arrow). This abnormal position is caused by the action of the infrahyoid muscles. It strongly suggests associated injury of the suprahyoid muscles.

and denuded cartilages (Schaefer group 4); the laryngeal skeleton appears to be crushed. Most laryngeal injuries seen at imaging are Schaefer groups 2, 3 and 4 lesions, while Schaefer group 5 lesions are very rare [1–4].

7.3. Thyroid cartilage fractures

Laryngeal fractures may involve a single cartilage or multiple cartilages (up to 37% of cases) [7]. The thyroid cartilage is the most often involved cartilage. Depending on trauma mechanism, fractures may be unilateral or bilateral. Whenever the larynx is pushed against the spine, fracture lines in the thyroid cartilage are unilateral, vertically oriented and located in a median or paramedian position (Fig. 6). Horizontal fractures involving the thyroid cartilage are classically encountered in strangulation cases [5,42]. They are bilateral and typically involve the superior border of the thyroid laminae and the superior horns of the thyroid cartilage (Figs. 7 and 8). They are often associated with hyoid bone fractures and hypopharyngeal hematoma (Fig. 8). Horizontal fractures of the thyroid cartilage and fractures of the hyoid bone may be missed on axial CT images unless coronal ± sagittal oblique 2D MPR or 3D VR are performed [7]. The superiority of 3D VR for the detection of these fractures has also been recently shown in a post mortem study that compared the performance of MDCT with autopsy of strangulation victims: MDCT with 3D VR revealed fractures initially missed at autopsy [43]. The diagnosis of fractures of the hyoid bone and superior horns of the thyroid cartilage may be challenging in cases with multiple accessory cartilages or absent fusion of the cartilaginous joints between the greater horns and body of the hyoid bone [42]. In our own experience, the differentiation between a fractured superior horn of the thyroid cartilage and an accessory cartilage should be made on the basis of cartilage margins: sharply delineated borders suggest a recent fracture, whereas rounded borders rather suggest an accessory cartilage. In addition, a large hematoma surrounding the superior horn is a further indirect sign suggesting cartilage fracture (Figs. 2 and 8).

Whenever the inferior horns of the thyroid cartilage are fractured, crico-thyroid dislocation and cricoid fractures should be carefully looked for (Fig. 9). Crico-thyroid dislocation is diagnosed in the presence of an abnormal rotation between the two cartilages. However, in patients with improper positioning on the scan table, particular attention should be paid to the axis of the reconstructed images (see above).

7.4. Cricoid cartilage fractures

Fractures of the cricoid cartilage are less common than fractures of the thyroid [44]. They are often bilateral and may cause sudden airway obstruction. Most cricoid fractures are associated with fractures of other cartilages, isolated cricoid fractures being very rare [44]. Mucosal tears with cartilage exposure are seen in up to 50% of all cricoid fractures adding to respiratory insufficiency and promoting infection. As the cricoid cartilage is poorly ossified, these fractures may be overlooked at MDCT unless soft tissue windows are carefully analyzed or MRI is performed (Fig. 9). As opposed to the thyroid cartilage, 3D VR does not provide additional diagnostic information in these fractures (Fig. 9).

In up to 50% of cricoid fractures, partial or complete laryngo-tracheal separation may occur [45,46]. Delayed diagnosis of laryngo-tracheal separation is made in 40% of cases after the critical period [45]. Rupture of the trachea is typically seen at the level of the first tracheal ring [28]. In complete transection, the

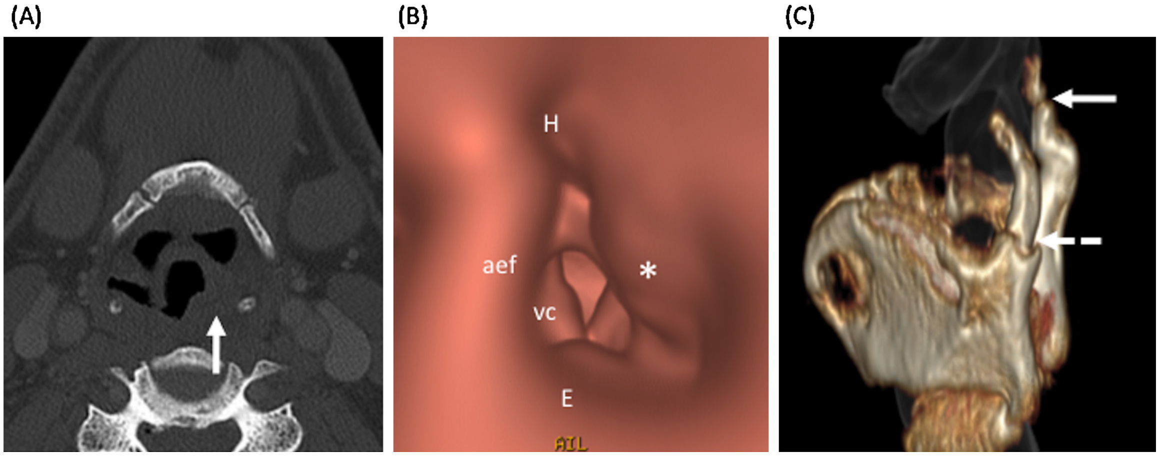

Fig. 8. Horizontal fracture of the thyroid cartilage and characteristic hypopharyngeal hematoma caused by strangulation. (A) Axial CT image shows left hypopharyngeal hematoma (arrow). Note slightly abnormal position of left superior horn of the thyroid cartilage, which is shifted toward the midline. (B) VE image (view from above) shows mass effect of hematoma (asterisk) on the supraglottic larynx. E, epiglottis; H, hypopharynx; aef, right aryepiglottic fold; vc, right vocal cord. (C) Multilayer 3D VR (left oblique view) shows bilateral fractures of the superior horns of the thyroid cartilage (beige). Airway rendered in semitransparent white. Right fracture (solid arrow). Left fracture (dashed arrow).

trachea retracts into the mediastinum. As the peritracheal fascia may remain intact, tracheal intubation may still be possible [47]. MDCT reveals widening of the crico-tracheal distance due to retraction of the trachea into the mediastinum and the endotracheal tube lies in an amorphous cavity caused by rupture of the crico-tracheal membrane [47]. The cranio-caudal gap between the trachea and the cricoid cartilage is best appreciated on coronal or sagittal 2D MPR. Massive subcutaneous emphysema in the absence of a significant pneumothorax is common. In incomplete rupture (Fig. 10), tracheal deformation and discontinuity, mucosal laceration, displacement of the endotracheal tube and emphysema are observed [28]. Complete and incomplete ruptures are often associated with burst fractures of the cricoid cartilage (Fig. 10). Incomplete tracheal ruptures need to be differentiated from pre-existing tracheal

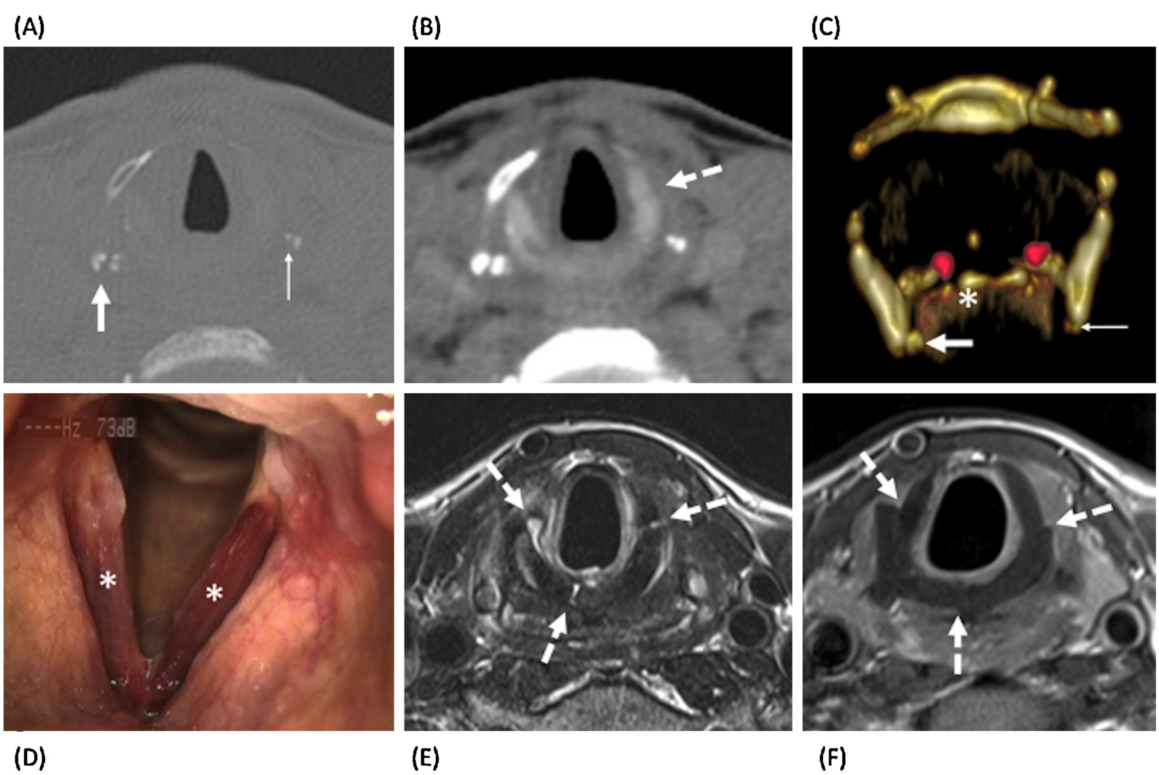

Fig. 9. Cricoid cartilage fracture suspected on CT and confirmed on MRI in a young female who fell on the stairs. (A) Axial bone window at the level of the subglottis shows bilateral fractures of the inferior horns of the thyroid cartilage (right fracture: thick arrow; left fracture: thin arrow). The cricoid cartilage cannot be assessed on this axial bone window. (B) Corresponding axial soft tissue window reveals a possible fracture line in the left cricoid cartilage (dashed arrow). (C) 3D VR (posterior view) depicts the hyoid bone, thyroid cartilage and cricoid cartilage in beige and the arytenoids in red. Fracture of the left inferior horn (thick arrow) and right inferior horn (thin arrow) of the thyroid cartilage. Note that the cricoid cartilage (asterisk) is poorly ossified and a fracture of the cricoid cannot be seen. (D) Flexible endoscopy shows bilateral glottic (asterisk) and subglottic hematoma and no mucosal laceration. T2w image (E) and T1w image after intravenous gadolinium (F) obtained at the same level as in (A and B) clearly show three fracture lines within the nonossified cricoid cartilage (dashed arrows). There is slight fragment displacement on the right, however the subglottic mucosa appears intact.

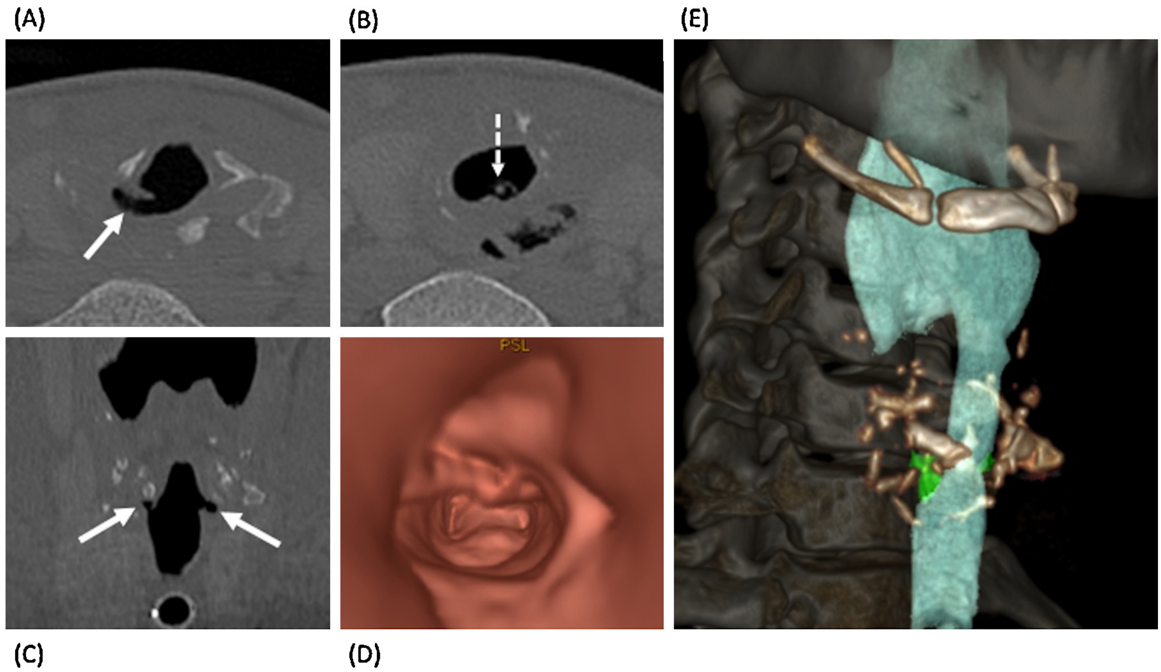

Fig. 10. Clothesline injury with burst fractures of the laryngeal cartilages and incomplete laryngo-tracheal separation. Axial (A and B), and coronal (C) 2D MPR images reveal shattered thyroid and cricoid with irregular mucosal pouches (arrows) bilaterally and mucosal fragments floating in the deformed tracheal lumen (dashed arrow). (D) VE image of the subglottic area and cervical trachea show multiple pseudo-pouches due to partial tracheal transection. Note major deformation of the cervical trachea. (E) Multilayer 3D VR image (right anterior oblique view) displays the hyoid bone and the shattered laryngeal cartilages in beige, and the airway column in blue. Trachea rupture sites with pseudo-diverticula are rendered in green. Incomplete laryngo-tracheal separation was confirmed at surgery.

diverticula, which may occasionally present with dyspnea and hoarseness due to compression of the recurrent laryngeal nerve by the diverticulum itself [48]. Tracheal diverticula are benign incidental findings seen on CT. They are located at the level of the thoracic inlet, on the right side, posteriorly to the membranous portion of the trachea [48].

Tearing and stretching of the recurrent laryngeal nerve is a feared associated injury in cricoid fractures and laryngo-tracheal separation. It has been reported in 60% of patients with complete tracheal transection [47]. Although some patients may recover satisfactory function of the recurrent laryngeal nerve, permanent palsy is common (see below).

7.5. Fractures of the arytenoid cartilages

Arytenoid fractures are the least common laryngeal fractures. They occur in association with fractures of the thyroid and cricoid (Fig. 3). Nearly 50% are bilateral. Arytenoid luxation is most often caused by intubation. However, it may also occur in external laryngeal trauma [3,7,49]. Arytenoid luxation is diagnosed on axial images and 2D MPR when the cricothyroid space is widened and whenever anterior or posterior displacement of the arytenoid is seen (Fig. 11). The degree of arytenoid rotation caused by luxation/subluxation is best assessed on 3D VR as the dislocated arytenoid typically shows anterior inferior or superior tilting of the vocal process and rotation of the arytenoid body [7,16,50]. 3D VR are superior to axial images and 2D MPR for the depiction of arytenoid rotation and tilting in up to 75% of cases with external laryngeal injury [7]. Arytenoid dislocation and subluxation need to be distinguished from recurrent laryngeal nerve paralysis [51,52]. On MDCT obtained during quiet respiration, recurrent laryngeal nerve paralysis displays enlargement of the ipsilateral laryngeal ventricle and piriform sinus, thickening and medial rotation of the ipsilateral aryepiglottic fold, anteromedial displacement of the arytenoid and medial displacement of the posterior vocal cord border [52]. Although imaging, in particular 3D VR, have been shown to be very useful in differentiating arytenoid dislocation and subluxation from recurrent laryngeal nerve paralysis [50], correlation with endoscopy remains essential [53] not only for diagnosis but also for early arytenoid repositioning surgery.

7.6. Injuries of the epiglottis, prelaryngeal strap muscles and hyoid bone

Avulsion of the epiglottis is rare and occurs when the thyroepiglottic ligament is torn. MDCT may miss this type of injury because the epiglottis is not ossified and because detection of hematoma within the pre-epiglottic space or around the petiole is a non-specific finding [34]. Although MRI may detect avulsion of the epiglottis [34], endoscopy is mandatory enabling both diagnosis and surgical repair.

In cases of strangulation or penetrating laryngeal trauma, the thyrohyoid membrane and the suprahyoid muscles may be torn. Due to the action of the infrahyoid muscles, the hyoid bone is pulled downwards. Although lesions of the thyrohyoid membrane and suprahyoid muscles cannot be directly seen at MDCT, an abnormally low position of the hyoid bone should raise the suspicion of such a lesion (Fig. 7). An abnormally low position of the hyoid bone may be suspected on axial MDCT images and on 2D MPR when the body of the hyoid is located anteriorly to the thyroid cartilage. It is, however, more easily seen on 3D VR (Fig. 7).

An abnormally high position of the hyoid bone has been reported in tracheal transection [54]. When a direct blow is applied to the hyperextended neck, the trachea may be ruptured and the infrahyoid muscles torn. As a consequence, the suprahyoid muscles pull the hyoid bone upwards which results in elevation of

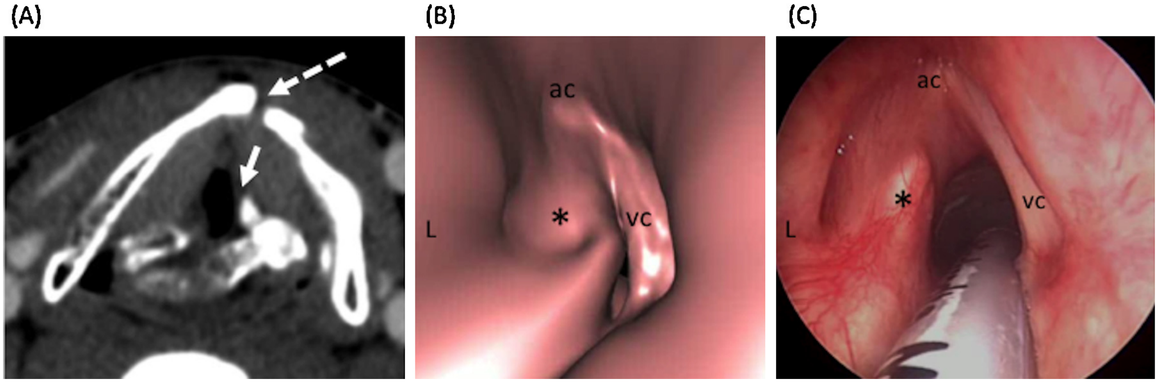

Fig. 11. Arytenoid luxation following dashboard injury. (A) Axial image shows slight widening of the left cricothyroid space and anterior displacement of the left arytenoid (arrow). Note associated thyroid fracture (dashed arrow). (B) VE image (view from above) shows deformation of the left vocal cord (asterisk) due to anterior–inferior dislocation of the arytenoid. ac, anterior commissure; vc, right vocal cord; L, left. (C) Corresponding endoscopic image confirms the radiologic findings revealing antero-inferior arytenoid dislocation (asterisk). ac, anterior commissure; vc, right vocal cord; L, left. Endoscopic arytenoid repositioning was successful.

the hyoid bone. Elevation of the hyoid bone is diagnosed on lateral X rays, sagittal 2D MPR or 3D VR when the position of the hyoid bone is above the third cervical vertebra [54]. As the clinical signs of a tracheal transection may be absent initially, a high index of suspicion is required when interpreting these images.

Although soft tissue emphysema is recognized as one of the most common indirect signs of laryngeal injury, a high percentage of patients with laryngeal fractures may not have soft tissue emphysema on MDCT [7]. Therefore, the absence of emphysema does not exclude laryngeal fractures and should not make the radiologist less alert when assessing CT data sets.

8. Imaging findings of long-term sequelae

The spectrum of long-term sequelae in laryngeal trauma is broad and ranges from minor deformation to post-traumatic synostosis between the larynx and cervical spine [55].

8.1. Post-traumatic cartilage deformation, pseudarthrosis and nodular chondrometaplasia

Cartilage deformation following laryngeal trauma can cause dyspnea or hoarseness necessitating endoscopy. During endoscopy, narrowing or asymmetry of the laryngeal lumen may be seen.

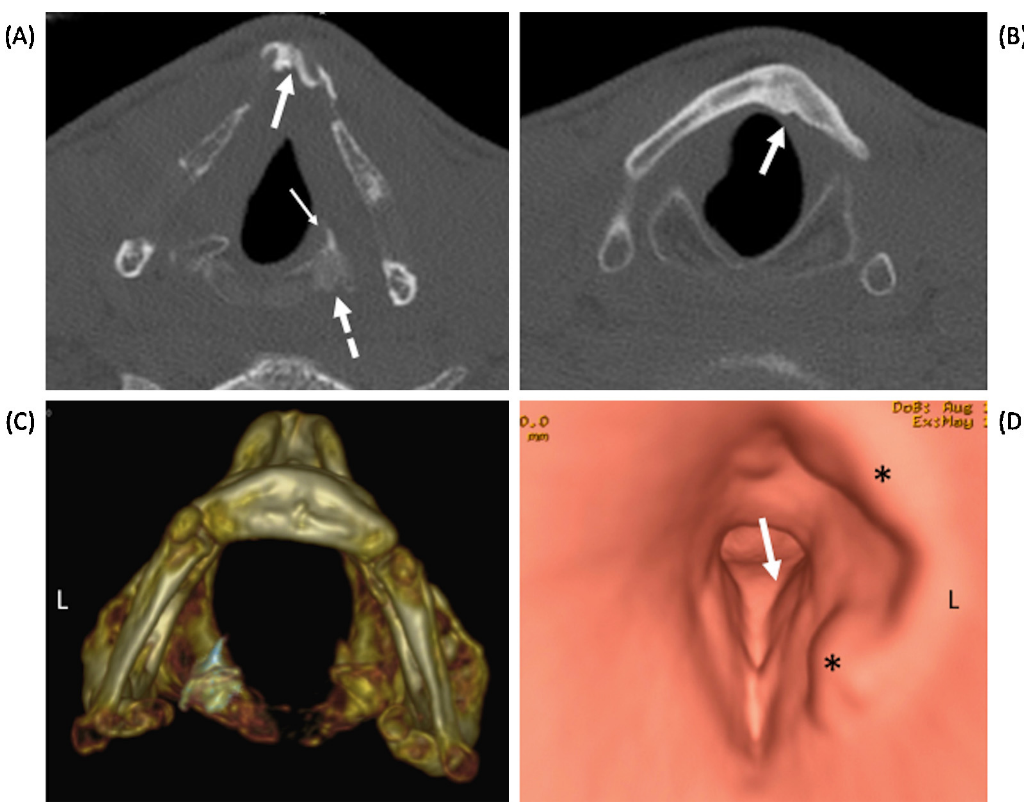

Fig. 12. Characteristic post-traumatic sequelae 5 years after laryngeal trauma. Axial images (A and B) show post-traumatic deformation of the anterior thyroid cartilage (arrows) with pseudarthrosis anteriorly (arrow in A). Crico-arytenoid ankylosis (dashed arrow) and post-traumatic ossification of the vocal process (thin arrow) are seen on the left. (C) 3D VR (view from above) depicting cartilages and hyoid bone in beige. The left arytenoid is rendered in blue. Note its pointed aspect anteriorly due to post-traumatic ossification of the vocal process. L = left. (D) VE image showing laryngeal airway deformation on the left (asterisks) and in the subglottis (arrow) due to post-traumatic cartilage deformation and scaring.

As the mucosa is intact, a submucosal mass may be suspected endoscopically. Imaging, however, allows differentiation between a submucosal tumor and post-traumatic deformation of ossified or non-ossified cartilages [56,57]. Post-traumatic changes in ossified cartilage include bone remodeling with callus formation or pseudarthrosis (Fig. 12). Post-traumatic changes in non-ossified cartilage include bending or – less often – nodular chondrometaplasia. Nodular chondrometaplasia is a distinct histologic entity characterized by proliferation of fibroelastic cartilage surrounded by a thin rim of fibrous tissue [58]. Although most nodular chondrometaplasia lesions are small, occasionally, the nodules may become larger than 1 cm, constituting a diagnostic challenge. A well-defined bulky nodule arising within the laryngeal cartilages is typically seen on CT or MRI displaying similar imaging features as chondromas or low-grade chondrosarcomas [56]. However, the patient's history of previous trauma should raise the suspicion of post-traumatic chondrometaplasia [58].

Pseudarthrosis as a complication of laryngeal trauma results from impaired healing of a laryngeal fracture. It has been reported in the superior horns of the thyroid cartilage [37]. Most often, the accidents causing this type of injury are trivial and the affected patients rarely associate them with their symptoms [37]. Pain typically occurs when the fracture ends rub against each other during swallowing or breathing [37].

8.2. Crico-arytenoid ankylosis

Crico-arytenoid ankylosis may be caused by a variety of conditions, such as ankylosing spondyloarthritis, recurrent laryngeal nerve palsy, radiation therapy, intubation or, less often, external laryngeal trauma (Fig. 12). CT findings of crico-arytenoid ankylosis comprise narrowing of the crico-arytenoid joint, subchondral sclerosis and fixation of the arytenoid. Although the CT aspect alone cannot be assigned to any of the above-mentioned causes, the combination of patient history and radiologic findings allows the diagnosis of posttraumatic ankylosis (Fig. 12).

8.3. Subglottic stenosis

In over 92% of cases, acquired subglottic stenosis is caused by intubation; in less than 5%, it is caused by external laryngeal trauma [59]. Following edema, hematoma and ulceration, granulation tissue forms which may result in chondritis of the cricoid. Tissue repair leads to scar formation with subsequent stenosis. Symptoms usually manifest 1 year or later after trauma and include dyspnea, stridor, hoarseness or cyanosis. On MDCT, subglottic and upper tracheal narrowing caused by circumferential soft tissue thickening are observed. The cricoid cartilage and the trachea may display dystrophic calcifications, deformation or fragmentation. Mucosal pouches mimicking true diverticula are seen on VE and 3D VR. Although axial images are sufficient for the diagnosis, 2D MPR in the coronal or sagittal plane are indispensable for surgical planning allowing accurate assessment of cranio-caudal extent.

8.4. Post-traumatic granuloma

Granulomas, most often referred to as contact ulcers, typically occur after intubation or due to tuberculosis, sarcoidosis or gastroesophageal reflux. Rarely, granulomas may develop after external laryngeal trauma [60]. Pyogenic granulomas are a histologically distinct granuloma type displaying morphologic features both of contact ulcers and of capillary hemangiomas. They are caused by blunt laryngeal trauma and may manifest with near total airway obstruction and spontaneous intralaryngeal bleeding [60]. Imaging shows a well-delineated polypoid and hypervascular mass.

8.5. Other complications

Palsy of the recurrent laryngeal nerve constitutes a feared long-term complication of laryngeal trauma. Its recognition is straightforward on CT (see above) [52].

Post-traumatic synostosis between the larynx and the cervical spine is a rare complication of laryngeal trauma; the suggested mechanism is heterotopic ossification induced by diminished local motility and scarring [55]. Heterotopic bony bridging between the thyroid cartilage and the transverse process of the cervical vertebrae may lead to impaired or absent laryngeal elevation during swallowing with subsequent dysphagia and aspiration [55].

9. Management of laryngeal trauma

Initial management of laryngeal trauma focuses on airway evaluation and stabilization, as well as patient triage in the appropriate severity group (Table 1). The best method to establish airway patency has not been resolved, but most otolaryngologists prefer cricothyrotomy or tracheostomy rather than endotracheal intubation [2] because intubation may further damage the larynx and may interfere with subsequent examination and repair.

Conservative laryngeal management is feasible when the laryngeal framework is stable and the airways are patent. Schaefer type 1 and occasionally Schaefer type 2 lesions (Table 1) respond to conservative measures such as voice rest, inhalation with humidified oxygen, head elevation, and proton pump inhibitors [4–6]. Round the clock monitoring in a specialized unit and serial observations with flexible endoscopy are mandatory.

Open reduction and internal fixation for non-displaced fractures (Schaefer type 2) are increasingly performed in many centers because even minor cartilage displacement near the anterior commissure may result in long term voice impairment. Dislocated laryngeal fractures (Schaefer types 3 and 4) are often repaired surgically using mini-plates [4–6,14]. Laryngeal reconstruction with mini-plates (Fig. 6) is well tolerated and improves functional results, with a reduction in hospital stay, good long-term airway patency and good voice quality [4–6,14]. Major endolaryngeal soft tissue injury (vocal ligament avulsion, epiglottis detachment, arytenoid dislocation) is managed either via thyrotomy or endoscopically. An instable larynx (Schafer type 4) mandates the use of a stent to allow healing of soft tissues in the appropriate shape and position. Stents of triangular shape and soft materials are preferred and left in place for a few months.

As in other trauma situations, surgical repair should take place within a few days to achieve the best functional results. Some authors advocate open laryngeal surgery within the first 24 h while others recommend surgical exploration to be performed 3–5 days later allowing edema to resolve. According to the literature, early surgery decreases voice and airway complications by up to 40% [4–6,11,14,59].

10. Conclusions

Trauma of the anterior neck may result in various injuries of the laryngeal soft tissues, cartilages and surrounding structures. MDCT is used as a first line examination in the acute trauma setting. It plays a vital role for the rapid and accurate detection of laryngeal injuries, and associated brain, face, vascular, cervical spine or distant lesions. Although axial MDCT images may detect most fractures of the cartilaginous skeleton, the use of 2D MPR and 3D VR is of major help for the assessment of horizontal fractures of the thyroid cartilage and of the hyoid bone. 3D VR are particularly useful for the diagnosis of arytenoid luxation while VE provide fly through images similar to endoscopy facilitating interdisciplinary communication and treatment planning. MRI is used as a second line approach. It is superior to MDCT for the assessment of fractures involving non-ossified cartilages or epiglottic avulsion. Both modalities also play an important role for the evaluation of post-traumatic lesions in the larynx.

Conflict of interest

We herewith confirm that all authors and authors' institutions have no conflicts of interest, nor any financial interest with respect to the above-mentioned manuscript.

References

[1] Schaefer SD. Use of CT scanning in the management of the acutely injured larynx. Otolaryngol Clin North Am 1991;24(1):31–6.
[2] Schaefer SD. The acute management of external laryngeal trauma. A 27-year experience. Arch Otolaryngol Head Neck Surg 1992;118(6):598–604.
[3] Robinson S, Juutilainen M, Suomalainen A, Makitie AA. Multidetector row computed tomography of the injured larynx after trauma. Semin Ultrasound CT MR 2009;30(3):188–94.
[4] Juutilainen M, Vintturi J, Robinson S, Back L, Lehtonen H, Makitie AA. Laryngeal fractures: clinical findings and considerations on suboptimal outcome. Acta Otolaryngol 2008;128(2):213–8.
[5] Jewett BS, Shockley WW, Rutledge R. External laryngeal trauma analysis of 392 patients. Arch Otolaryngol Head Neck Surg 1999;125(8):877–80.
[6] Jalisi S, Zoccoli M. Management of laryngeal fractures—a 10-year experience. J Voice 2011;25(4):473–9.
[7] Becker M, Duboé PO, Platon A, et al. Assessment of laryngeal trauma with MDCT: value of 2D multiplanar and 3D reconstructions. AJR Am J Roentgenol 2013;201:W639–47.
[8] Mancuso AA, Hanafee WN. Computed tomography of the injured larynx. Radiology 1979;133(1):139–44.
[9] Becker M, Burkhardt K, Dulguerov P, Allal A. Imaging of the larynx and hypopharynx. Eur J Radiol 2008;66(3):460–79.
[10] Glastonbury CM. Non-oncologic imaging of the larynx. Otolaryngol Clin North Am 2008;41(1):139–56, vi.
[11] Mandel JE, Weller GE, Chennupati SK, Mirza N. Transglottic high frequency jet ventilation for management of laryngeal fracture associated with air bag deployment injury. J Clin Anesth 2008;20(5):369–71.
[12] Lee KS, Boiselle PM. Update on multidetector computed tomography imaging of the airways. J Thorac Imaging 2010;25(2):112–24.
[13] Wintermark M, Poletti PA, Becker CD, Schnyder P. Traumatic injuries: organization and ergonomics of imaging in the emergency environment. Eur Radiol 2002;12(May (5)):959–68.
[14] Bell RB, Verschueren DS, Dierks EJ. Management of laryngeal trauma. Oral Maxillofac Surg Clin North Am 2008;20(3):415–30.
[15] Meglin AJ, Biedlingmaier JF, Mirvis SE. Three-dimensional computerized tomography in the evaluation of laryngeal injury. Laryngoscope 1991;101(2):202–7.
[16] Mau T. Three-dimensional morphometric analysis of cricoarytenoid subluxation. J Voice 2012;26(2):133–6.
[17] Mupparapu M, Vuppalapati A. Ossification of laryngeal cartilages on lateral cephalometric radiographs. Angle Orthod 2005;75(2):196–201.
[18] Castelijns JA, Becker M, Hermans R. Impact of cartilage invasion on treatment and prognosis of laryngeal cancer. Eur Radiol 1996;6(2):156–69.
[19] Hatley W, Samuel E, Evison G. The pattern of ossification in the laryngeal cartilages: a radiological study. Br J Radiol 1965;38:585–91.
[20] Jurik AG. Ossification and calcification of the laryngeal skeleton. Acta Radiol Diagn (Stockh) 1984;25(1):17–22.
[21] Zan E, Yousem DM, Aygun N. Asymmetric mineralization of the arytenoid cartilages in patients without laryngeal cancer. AJNR Am J Neuroradiol 2011;32(6):1113–8.
[22] Miller RH, Duplechain JK. Penetrating wounds of the neck. Otolaryngol Clin North Am 1991;24(1):15–29.
[23] Grewal H, Rao PM, Mukerji S, Ivatury RR. Management of penetrating laryngotracheal injuries. Head Neck 1995;17(6):494–502.
[24] Bell RB, Osborn T, Dierks EJ, Potter BE, Long WB. Management of penetrating neck injuries: a new paradigm for civilian trauma. J Oral Maxillofac Surg 2007;65(4):691–705.
[25] Bhojani RA, Rosenbaum DH, Dikmen E, et al. Contemporary assessment of laryngotracheal trauma. J Thorac Cardiovasc Surg 2005;130(2):426–32.
[26] Atkins BZ, Abbate S, Fisher SR, Vaslef SN. Current management of laryngotracheal trauma: case report and literature review. J Trauma 2004;56(1):185–90.
[27] Kuttenberger JJ, Hardt N, Schlegel C. Diagnosis and initial management of laryngotracheal injuries associated with facial fractures. J Craniomaxillofac Surg 2004;32(2):80–4.
[28] Scaglione M, Romano S, Pinto A, Sparano A, Scialpi M, Rotondo A. Acute tracheobronchial injuries: impact of imaging on diagnosis and management implications. Eur J Radiol 2006;59(3):336–43.
[29] Corneille MG, Stewart RM, Cohn SM. Upper airway injury and its management. Semin Thorac Cardiovasc Surg 2008;20(1):8–12.
[30] Stanley Jr RB. Value of computed tomography in management of acute laryngeal injury. J Trauma 1984;24(4):359–62.
[31] Lupetin AR, Hollander M, Rao VM. CT evaluation of laryngotracheal trauma. Semin Musculoskelet Radiol 1998;2(1):105–16.
[32] Steenburg SD, Sliker CW, Shanmuganathan K, Siegel EL. Imaging evaluation of penetrating neck injuries. Radiographics 2010;30(4):869–86.
[33] Laroia AT, Thompson BH, Laroia ST, van Beek Jr E. Modern imaging of the tracheo-bronchial tree. World J Radiol 2010;2(7):237–48.
[34] Duda Jr JJ, Lewin JS, Eliachar IMR. evaluation of epiglottic disruption. AJNR Am J Neuroradiol 1996;17(3):563–6.
[35] Faden DL, Elackatuu A, The Platt M. closed-airway sneeze: an unusual cause of laryngeal fracture. Otolaryngol Head Neck Surg 2011;145(3):515–6.
[36] Bockholdt B, Hempelmann M, Maxeiner H. Experimental investigations of fractures of the upper thyroid horns. Leg Med (Tokyo) 2003;5(Suppl. 1):S252–5.
[37] Knopke S, Todt I, Ernst A, Seidl RO. Pseudarthroses of the cornu of the thyroid cartilage. Otolaryngol Head Neck Surg 2010;143(2):186–9.
[38] MacFarlane P, Stranz C, MacKay S. Missed laryngotracheal rupture leading to delayed presentation. ANZ J Surg 2008;78(11):1030–1.
[39] Fuhrman GM, Stieg 3rd FH, Buerk CA. Blunt laryngeal trauma: classification and management protocol. J Trauma 1990;30(1):87–92.
[40] Verschueren DS, Bell RB, Bagheri SC, Dierks EJ, Potter BE. Management of laryngo-tracheal injuries associated with craniomaxillofacial trauma. J Oral Maxillofac Surg 2006;64(2):203–14.
[41] Kohler R, Vargas MI, Masterson K, Lovblad KO, Pereira VM, Becker M. CT and MRI angiography features of traumatic vascular injuries of the neck. AJR Am J Roentgenol 2011;196(6):W800–9.
[42] Green H, James RA, Gilbert JD, Byard RW. Fractures of the hyoid bone and laryngeal cartilages in suicidal hanging. J Clin Forensic Med 2000;7(3):123–6.
[43] Kempter M, Ross S, Spendlove D, et al. Post-mortem imaging of laryngohyoid fractures in strangulation incidents: first results. Leg Med (Tokyo) 2009;11(6):267–71.
[44] Oh JH, Min HS, Park TU, Lee SJ, Kim SE. Isolated cricoid fracture associated with blunt neck trauma. Emerg Med J 2007;24(7):505–6.
[45] Couraud L, Velly JF, Martigne C, N'Diaye M. Post traumatic disruption of the laryngo-tracheal junction. Eur J Cardiothorac Surg 1989;3(5):441–4.
[46] McCrystal DJ, Bond C. Cricotracheal separation: a review and a case with bilateral recovery of recurrent laryngeal nerve function. J Laryngol Otol 2006;120(6):497–501.
[47] Bowley DM, Plani F, Murillo D, Smith M, Degiannis E. Intubated, ventilating patients with complete tracheal transection: a diagnostic challenge. Ann R Coll Surg Engl 2003;85(4):245–7.
[48] Caversaccio MD, Becker M, Zbaren P. Tracheal diverticulum presenting with recurrent laryngeal nerve paralysis. Ann Otol Rhinol Laryngol 1998;107(4):362–4.
[49] Rubin AD, Hawkshaw MJ, Moyer CA, Dean CM, Sataloff RT. Arytenoid cartilage dislocation: a 20-year experience. J Voice 2005;19(4):687–701.
[50] Hiramatsu H, Tokashiki R, Kitamura M, Motohashi R, Tsukahara K, Suzuki M. New approach to diagnose arytenoid dislocation and subluxation using three-dimensional computed tomography. Eur Arch Otorhinolaryngol 2010;267(12):1893–903.
[51] Storck C, Buitrago-Tellez C. Multidetector computed tomography in non-malignant laryngeal disease. Curr Opin Otolaryngol Head Neck Surg 2012;20(6):443–9.
[52] Paquette CM, Manos DC, Psooy BJ. Unilateral vocal cord paralysis: a review of CT findings, mediastinal causes, and the course of the recurrent laryngeal nerves. Radiographics 2012;32(3):721–40.
[53] Kosling S, Heider C, Bartel-Friedrich S. CT findings in isolated laryngeal trauma. Laryngorhinootologie 2005;84(8):583–8.
[54] Polansky A, Resnick D, Sofferman RA, Davidson TM. Hyoid bone elevation: a sign of tracheal transection. Radiology 1984;150(1):117–20.
[55] Han IH, Choi BK, Wang SG, Lee JC. Posttraumatic synostosis between the thyroid cartilage and the cervical spine causing dysphagia. Am J Otolaryngol 2012;33(3):358–60.
[56] Becker M, Moulin G, Kurt AM, et al. Non-squamous cell neoplasms of the larynx: radiologic–pathologic correlation. Radiographics 1998;18(5):1189–209.
[57] Becker M, Moulin G, Kurt AM, et al. Atypical squamous cell carcinoma of the larynx and hypopharynx: radiologic features and pathologic correlation. Eur Radiol 1998;8(9):1541–51.
[58] Orlandi A, Fratoni S, Hermann I, Spagnoli LG. Symptomatic laryngeal nodular chondrometaplasia: a clinicopathological study. J Clin Pathol 2003;56(12):976–7.
[59] Couraud L, Jougon JB, Velly JF. Surgical treatment of nontumoral stenoses of the upper airway. Ann Thorac Surg 1995;60(2):250–9, discussion 9-60.
[60] Garrett MM, Lee WT. Obstructing pyogenic granuloma as a result of blunt laryngeal trauma. Otolaryngol Head Neck Surg 2007;136(3):489–90.