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Ultrasound for airway management: An evidence-based review for the emergency clinician☆,☆☆

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ABSTRACT

Background: Airway management is a common procedure performed in the Emergency Department with significant potential for complications. Many of the traditional physical examination maneuvers have limitations in the assessment and management of difficult airways. Point-of-care ultrasound (POCUS) has been increasingly studied for the evaluation and management of the airway in a variety of settings.
Objective: This article summarizes the current literature on POCUS for airway assessment, intubation confirmation, endotracheal tube (ETT) depth assessment, and performing cricothyroidotomy with an emphasis on those components most relevant for the Emergency Medicine clinician.
Discussion: POCUS can be a useful tool for identifying difficult airways by measuring the distance from the skin to the thyrohyoid membrane, hyoid bone, or epiglottis. It can also predict ETT size better than age-based formulae. POCUS is highly accurate for confirming ETT placement in adult and pediatric patients. The typical approach involves transtracheal visualization but can also include lung sliding and diaphragmatic elevation. ETT depth can be assessed by visualizing the ETT cuff in the trachea, as well as using lung sliding and the lung pulse sign. Finally, POCUS can identify the cricothyroid membrane more quickly and accurately than the landmark-based approach.
Conclusion: Airway management is a core skill in the Emergency Department. POCUS can be a valuable tool with applications ranging from airway assessment to dynamic cricothyroidotomy. This paper summarizes the key literature on POCUS for airway management.

1. Introduction

Resuscitation of critically ill patients in the Emergency Department (ED) involves rapid airway assessment and potentially definitive airway management. Endotracheal intubation is a commonly performed procedure by Emergency Medicine (EM) physicians, with nearly 350,000 cases occurring each year in the United States alone [1]. Approximately 10% of cases requiring emergent airway management are considered difficult intubations [2]. Urgent airway intervention carries a risk of complications that can lead to severe morbidity and mortality. A multicenter study of intubations in the ED demonstrated a 12% incidence of complications and adverse events including esophageal intubation, mainstem intubation, hypotension, and cardiac arrest [3].

Ultrasound has been increasingly studied as a potential modality for airway assessment and management. Point-of-care ultrasound (POCUS) use is well established in the ED, both as a diagnostic tool and as an imaging guide for a variety of procedures. Emergency Medicine physicians consider ultrasound a fundamental component of resuscitation and have demonstrated high diagnostic accuracy in a number of applications including trauma, cardiac, and aorta imaging [4]. Therefore, it is not surprising that sonographic techniques have been adopted for emergent evaluation of the upper airway. Ultrasound can assist the physician in identifying relevant anatomy including bone and soft tissues of the hypopharynx and anterior neck, cricothyroid membrane, tracheal cartilages, esophagus, and aerated lung in a simple, rapid, and non-invasive manner.

POCUS can be applied to multiple aspects of airway management (Table 1). Sonographic measurements may play a role in identifying patients with a difficult airway prior to procedural sedation or an intubation attempt. Additionally, ultrasound can identify proper placement of the endotracheal tube (ETT), which is particularly valuable in clinical scenarios where confirmation with end-tidal capnography may be

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Table 1
Applications of ultrasound for airway management.

Assessing the airway
Identifying the difficult airway
Identifying subglottic stenosis
Predicting pediatric ETT size
Confirming intubation
Direct assessment with transtracheal visualization
Indirect assessment with lung sliding or diaphragmatic movement
Assessing ETT depth
Direct assessment with transtracheal visualization with or without a saline-filled ETT cuff
Indirect assessment with lung sliding or the lung pulse sign
Cricothyroidotomy
Identifying the cricothyroid membrane

ETT, endotracheal tube.

unreliable (e.g., cardiac arrest) [5,6]. After tracheal intubation is confirmed, ultrasound may then be used to confirm proper ETT depth. In those patients where airway complications are anticipated, ultrasound can also localize the cricothyroid membrane in preparation for a "cannot intubate, cannot ventilate" situation. This article will examine the use of ultrasound for airway management with an emphasis on those most relevant to the EM clinician.

2. Methods

The authors searched PubMed and Google Scholar for articles using a combination of the keywords "ultrasound", "airway", "intubation", "cricothyrotomy", and "cricothyroidotomy". Authors included case reports and series, retrospective and prospective studies, systematic reviews and meta-analyses, clinical guidelines, and other narrative reviews. The literature search was restricted to studies published in English. Emergency Medicine physicians with experience in critical appraisal of the literature reviewed all of the articles and decided which studies to include for the review by consensus, with a focus on EM-relevant articles. When available systematic reviews and meta-analyses were preferentially selected, followed sequentially by randomized controlled trials, prospective studies, retrospective studies, case reports, and other narrative reviews when alternate data were not available.

3. Assessing the airway

It has been reported that approximately 8–13% of difficult intubations are seen in the prehospital setting, intensive care unit, and ED [7,8]. Therefore, it is essential for practitioners to promptly assess and recognize potentially difficult airways prior to any intervention, so that appropriate equipment and resources are available [9].

In clinical practice, the initial approach to airway evaluation starts with bedside assessments (e.g., LEMON criteria, Mallampati score), which are performed to predict difficult airways [10,11]. However, while these tools are commonly used in the pre-operative setting, their use may be limited in the ED setting due to neck immobility, inability to follow commands, or concurrent use of non-invasive ventilation [12,13]. In fact, studies have found that the Mallampati Score is only 51–53% sensitive for predicting difficult laryngoscopy and 17% sensitive for predicting difficult bag-valve-mask ventilation [14,15]. Moreover, the Mallampati score also has poor reliability with kappa values ranging from 0.10 to 0.64 [14]. Among obese patients, these tools may have even worse diagnostic accuracy [16]. Consequently, experts have recommended that bedside physical examination airway assessments be used with caution due to the poor overall sensitivity of these tools [15].

This has led researchers to evaluate the role of POCUS as a potential tool for airway assessment. Several different sonographic parameters have been used to predict difficult intubations, with increased soft tissue depths associated with more difficult intubations. One study found that the distance from the skin to the vocal cords (2.8 cm vs 1.75 cm) and from the skin to the suprasternal notch were both highly predictive of difficult intubations (3.3 cm vs 2.7 cm) [17]. Another study found that the distance from the skin to the thyrohyoid membrane (3.5 cm vs 2.4 cm) was predictive of difficult intubations and recommended a threshold of greater than 2.8 cm to identify difficult intubations [18]. In this study, Adhikari and colleagues found that POCUS also outperformed standard clinical decision rules [18]. Wu and colleagues suggested that the distance from the skin to the hyoid bone (1.51 cm vs 0.98 cm) and the skin to the epiglottis (2.39 vs 1.49 cm) predicted difficult intubation [19]. However, a more recent study assessing these parameters was not able to identify a statistically significant difference for either the distance to the hyoid bone or distance to the epiglottis [20]. Interestingly, the distance from the skin to the epiglottis was predictive of difficult bag-valve-mask ventilation [20]. POCUS has also been found to be useful for evaluating for epiglottitis and epiglottal enlargement, which can be valuable in patients with concern for this [21-23]. Recently, Hall and colleagues proposed a potential ED airway assessment examination using POCUS which includes the following measurements: tongue base, tongue base-to-skin, epiglottic width and thickness, and pre-epiglottic space [24]. This was found to have good inter-rater reliability and correlated well with the Mallampati score [24]. However, further studies are needed to determine the predictive value of this approach among patients with a difficult airway.

In addition to the above parameters, POCUS can also be used to evaluate for subglottic stenosis and predict proper ETT size. Subglottic stenosis can be determined by measuring the inner diameter of the cricoid cartilage and tracking it inferiorly to identify the smallest area. Studies have demonstrated that POCUS is highly accurate for measuring airway size when compared with computed tomography and magnetic resonance imaging [25,26]. Among pediatric patients, POCUS is consistently more accurate than traditional age-based (i.e., age/4 + 4) and length-based formulas [27-30]. To begin, the transducer is placed in a transverse orientation on the neck and slid inferiorly to identify the cricoid cartilage. Then, the clinician slides the probe to the inferior aspect of the cricoid cartilage and measures the transverse air-column diameter (Fig. 1). Finally, the clinician uses this measurement to select the corresponding ETT based upon the outer diameter of the ETT (adjusting for cuffed versus uncuffed). Ultrasound has been found to be 88% to 100% accurate for predicting the correct ETT size [27-30]. By comparison, one study found that age-based was 35% accurate for cuffed ETT and 60% accurate for uncuffed ETT [27], while another found that overall accuracy for age-based was as low as 27% [29].

While there is not a single best approach to assessment of the difficult airway, the authors recommend that clinicians consider using POCUS to assess for higher risk features when predicting difficult

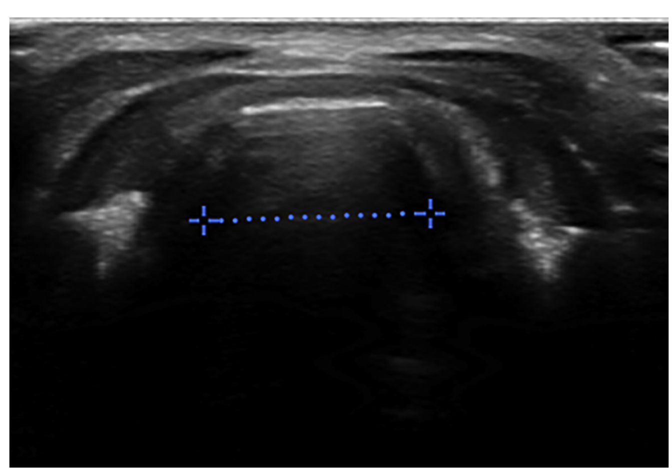

Fig. 1. Sonographic measurement of the trans-cricoid space for predicting pediatric ETT size.

intubations and measuring the subglottal diameter for identifying the ETT size in pediatric patients when feasible.

4. Confirming intubation

After performing an intubation, it is important to ensure the ETT is in the correct location, as studies have demonstrated that approximately 3.3% of all emergency intubations are esophageal [3]. Esophageal intubation, particularly when not promptly recognized, can result in significant morbidity and mortality [31]. Confirmation of correct ETT placement traditionally involves direct visualization of ETT passage through the vocal cords followed by a confirmatory technique [31]. Bilateral breath sounds, ETT misting, and the esophageal detector devices are not reliable enough to definitively confirm the location of the ETT [5,6,32-34]. Other devices, such as colorimetric and quantitative capnography, can be less reliable in patients with prior bag-valve-mask use or recent ingestion of a carbonated beverage, as well as when there is a paucity of carbon dioxide produced (e.g., cardiac arrest, pulmonary embolism, or significant pulmonary edema) [6,35]. In fact, studies have found that quantitative waveform capnography is only 60% to 68% sensitive for identifying endotracheal intubation during cardiac arrest [5,6,34]. Additionally, these devices require at least five breaths for confirmation, which can lead to gastric distention causing reduced gas exchange in pediatric patients and increased risk of aspiration [6,32].

POCUS has been increasingly recognized as a valuable adjunct for ETT confirmation with several recent systematic reviews demonstrating that it is highly accurate for ETT confirmation [36-40]. Among adult patients, transtracheal ultrasound is 98.7% sensitive and 97.1% specific [36]. Among pediatric patients, transtracheal ultrasound is 92–100% sensitive and 100% specific [40]. Studies have found that the accuracy remains consistent regardless of ETT size or transducer type (i.e., linear vs curvilinear) [41,42]. Additionally, it has been suggested that the learning curve for identifying ETT placement using POCUS is relatively short [43].

When performing transtracheal ultrasound, it is generally recommended to place the transducer in a transverse plane at the level of the suprasternal notch, as this has been demonstrated to have the best visualization and diagnostic accuracy when compared with other locations [44,45]. While the exact confirmatory finding can vary slightly between studies, most use one of three findings (Table 2) [36]. Among these, the most commonly utilized finding is the "double tract" sign (Figs. 2 and 3), which offers the advantage of being reliable in both static and dynamic assessments [36]. Static assessment refers to evaluation of the ETT location after the intubation has been performed, while dynamic assessment is performed concurrently with the intubation attempt. The current literature does not demonstrate a statistically significant difference in the diagnostic accuracy between static and dynamic techniques [36,46]. Advantages of the static technique include that only one provider is needed (i.e., the intubating provider can also perform the post-intubation assessment) and it avoids placing pressure on the patient's neck during the intubation, which could make the intubation more challenging. However, the advantages of the dynamic technique are that it may be easier to see the ETT due to the movement as it passes through the esophagus or trachea.

Table 2
Sonographic findings for transtracheal assessment of ETT location [36].

Sonographic finding	Description
"Double Tract" sign	When the ETT is within the trachea, there will be a single air-mucosa interface (Fig. 2). When the ETT is within the esophagus, there will be two air-mucosa interfaces (Fig. 3).
"Snowstorm" sign	When the ETT is passed through the trachea, a brief flutter of movement will be visualized within the tracheal rings. *Note: This finding will only be identified during a real-time, dynamic ultrasound examination.*
"Bullet" sign	When the ETT is within the trachea, the vocal cords and cricothyroid area will convert from a triangular shape to a round shape.

ETT, endotracheal tube.

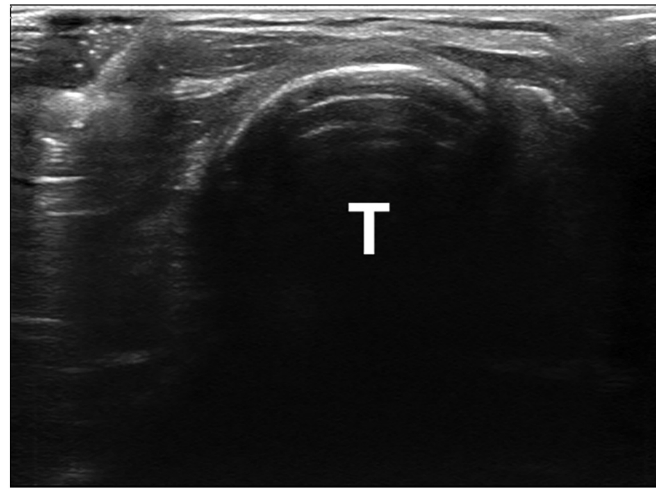

Fig. 2. Sonographic appearance of a tracheal intubation. *T* = *Trachea*.

Consequently, some authors have recommended twisting the ETT side-to-side after the intubation attempt to improve visualization during static ETT assessment [41,42,47 98]. When performing this technique, it is recommended to remove the stylet, as this has not been shown to improve the accuracy of ETT identification [48]. The use of color Doppler to facilitate ETT location identification has also been suggested, though it has not been demonstrated to improve the diagnostic accuracy over grayscale alone [49]. Other authors have suggested that inflating the ETT cuff with saline may improve the ability to identify ETT location, but further studies are needed [50,51].

Some experts have suggested using indirect signs, such as bilateral lung sliding or diaphragmatic elevation for intubation confirmation. Studies have found that bilateral lung sliding is 92% to 100% sensitive and 56% to 100% specific for ETT confirmation [52-57]. Meanwhile, diaphragmatic elevation has been demonstrated to be 91% to 100% sensitive and 50% to 100% specific for ETT placement confirmation [58-60]. However, when combined with transtracheal ultrasound, the diagnostic accuracy was significantly improved [56,61,62], with two studies

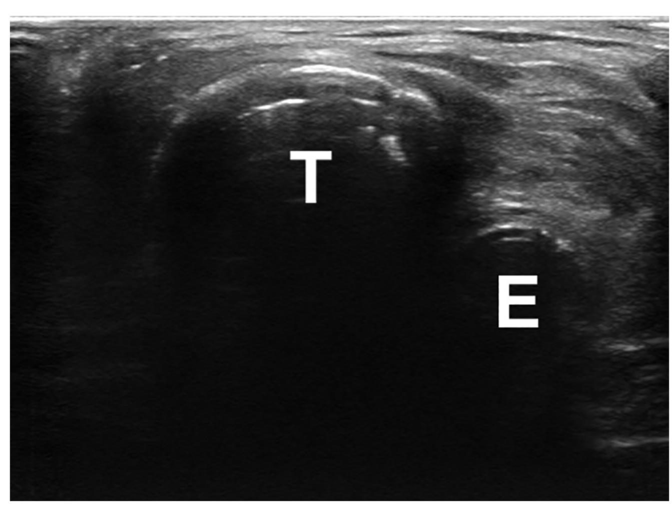

Fig. 3. Sonographic appearance of an esophageal intubation. *T* = *Trachea*; *E* = *Esophagus*.

finding that the combined approach was slightly better than either in isolation [54,55].

Importantly, ultrasound is one of several tools for intubation confirmation. While the diagnostic accuracy for transtracheal ultrasound is high, it is likely to be most effective when used in conjunction with other techniques, similar to auscultation and capnography.

5. Assessing endotracheal tube depth

Following confirmation of correct endotracheal placement, clinicians must ensure the ETT is inserted to the correct depth. Mainstem intubation is the most common complication, occurring in up to 8% of all intubations [63,64]. While it may not be noticed initially, this can result in significant barotrauma of the intubated lung, atelectasis of the contralateral lung, and worsening respiratory failure [65]. Alternatively, failing to insert the ETT far enough may result in the ETT becoming dislodged when the patient is repositioned during resuscitation. An ETT may become dislodged during completion of the primary or secondary survey, oral or nasogastric tube placement, positioning for portable chest radiographs or computed tomography, or transferring the patient from the ED stretcher to the operating room table or inpatient bed. Traditionally, clinicians utilize a series of routine practices to determine if the ETT is at the proper depth or has become dislodged. These include inserting the ETT to a pre-specified depth based upon the Broselow tape in pediatric patients or typical anatomic distances in adults (e.g., 21 cm in adult females and 23 cm in adult males), auscultating for symmetric bilateral lung sounds, and obtaining a post-intubation chest radiograph to confirm the location of the ETT tip [65-67]. However, anatomy can vary between patients and there can be significant time delays for obtaining a chest radiograph which limits rapid assessment when there is concern for dislodgement [68].

Analogous to confirmation of tracheal placement, ultrasound is also a useful adjunct to ensure adequate depth of ETT insertion. Recent studies have demonstrated that ultrasound is more sensitive and specific for assessing mainstem intubation than traditional auscultation [65], and more rapid than chest radiographs which may require up to 20 min to perform [51,52,60].

In neonates, the lack of sternal calcification can allow the ETT tip to be directly visualized in relation to intrathoracic structures [40,70-74]. Similar techniques to visualize the ETT tip have been reported with less accuracy and reliability in select adult populations due to the greater degree of calcification of the structures, as well as increased soft tissue depth [75,76]. As such, several alternative and novel strategies have been utilized to assess the ETT depth.

As early as 1987, Raphael and Conard first described the use of a saline-filled balloon at the sternal notch to identify ETT depth [77]. Introducing saline into the cuff provides a recognizable acoustic window within the otherwise obscuring shadows of the air-filled trachea (Fig. 4). Visualization of the ETT cuff balloon at the level of the sternal notch correlates with proper endotracheal depth [51,77]. This is best seen with the longitudinal view and may be enhanced with a slight 2-mm movement of the ETT in a cephalad to caudad direction or by using a standoff pad over the anterior neck when necessary [77]. More recently, a prospective feasibility study of 42 pediatric operating room patients reported a sensitivity of 98.8% and specificity of 96.4% for identifying mainstem intubation [69]. This latter study utilized a transverse view of the saline-filled cuff from the sternal notch, with a high kappa value between sonographers, and a mean identification time of only 4 s [69]. Additionally, Chen reported excellent sensitivity and specificity for confirming proper ETT depth by visualizing the superior aspect of the saline-filled cords within 1.9 to 4.1 cm of the vocal cords [78]. Novice sonographers may be able to learn this technique with reasonable accuracy after only a 50-minute training module [50]. While prior studies used saline, a recent study using an air-filled ETT cuff successfully identified the ETT in their cohort as well [65].

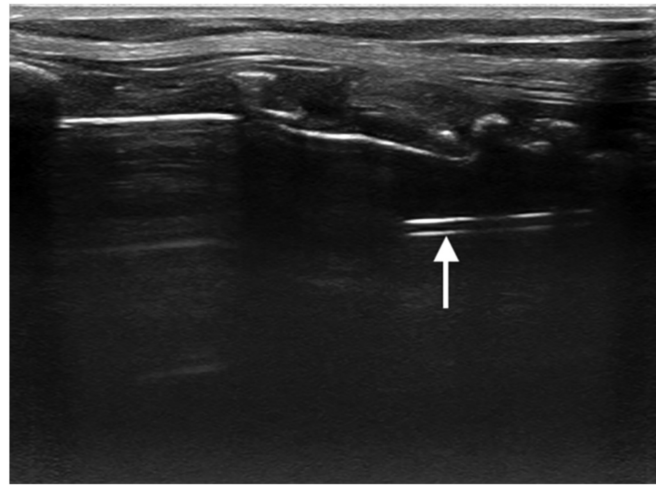

Fig. 4. Sonographic appearance of a saline-filled ETT cuff (arrow).

In addition to visualizing the ETT cuff itself, studies have also assessed for mainstem intubation using indirect measures. In both ED patients and cadaver models, investigators have demonstrated that right lung sliding in the absence of left lung sliding has a sensitivity of 69% to 92% and a specificity of 56% to 93% for predicting right mainstem intubation [52, 53]. Other investigators have combined lung sliding with visualization of the lung pulse. The lung pulse is created by cardiac contractions compressing against the atelectatic lung with normally opposed pleura and can help distinguish mainstem intubation from pneumothorax [79-81]. However, both of these findings depend on the presence of relatively normal pleura and may be limited when soft tissue air or pulmonary disease (e.g., large bullae, pleurodesis) are present [79-81].

As a single sonographic view is rarely obtained in isolation, the authors of this review recommend confirming proper depth of intubation by first visualizing the ETT cuff in the sternal notch, followed by assessing bilateral lung sliding or the presence of a lung pulse on the atelectatic side opposite the bronchial intubation.

6. Cricothyroidotomy

Cricothyroidotomy can be a life-saving procedure in “cannot intubate, cannot ventilate” situations. The most common complication of cricothyroidotomy is misplacement of the tube due to misidentification of the cricothyroid membrane, which can lead to disastrous consequences [82,83]. Classically, this technique was taught using surface landmarks to identify the cricothyroid membrane. However, first pass success rates with the landmark technique are as low as 36% among anesthesiologists [84]. A study of 20 EM physicians compared the accuracy of Seldinger versus surgical cricothyroidotomy in cadavers and found correct tube placement in 88% and 84%, respectively [85]. Landmark guidance alone is inadequate for the identification of the cricothyroid membrane and can be particularly difficult in obese patients [86,87]. A study by You-Ten and colleagues found that anesthesiologists were able to successfully identify the cricothyroid membrane with anatomical landmarks 71% of the time in non-obese women and only 39% of the time in obese women [88]. When compared with the landmark technique, ultrasound has been demonstrated to be superior for identifying the cricothyroid membrane [89,90]. In fact, one study demonstrated that ultrasound guidance during cricothyroidotomy resulted in a five-fold improvement in correct tube placement among subjects with difficult to palpate anatomy [91]. Landmark identification rates may be even lower in the time sensitive and potentially chaotic environment of a difficult intubation. Among patients with distorted neck anatomy, palpation was successful at identifying the cricothyroid membrane

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in only 8% of cases compared to 81% with ultrasound identification [92]. Moreover, one study found that EM physicians could reliably identify the cricothyroid membrane with ultrasound in a mean of 24 s [93].

In order to identify appropriate placement in the transverse plane, a linear probe is first placed on the midline of the neck at approximately the cricoid cartilage, with the probe indicator to the patient's right. The probe is slowly advanced cephalad until the thyroid cartilage is visualized as a hyperechoic, triangular structure (Fig. 5). The transducer is then moved caudally to visualize the cricothyroid membrane as a hyperechoic white line with reverberation air artifact posteriorly. To confirm visualization, the probe is advanced further caudally until the cricoid cartilage is visualized (Fig. 6). The probe can then be moved cephalad to again visualize the cricothyroid membrane. A skin marker can be used to mark the midline of the cricothyroid membrane above and below the probe if the procedure is being performed prior to intubation [86]. Alternatively, dynamic guidance can be performed by inserting a needle through the cricothyroid membrane under ultrasound visualization using a Seldinger technique. This dynamic technique was found to be superior to palpation alone with successful first pass in 87% of patients in the POCUS group compared to 58% of patients in the landmark group [94].

An alternative approach to the transverse technique described above is the longitudinal technique. Similar to the transverse approach, the linear probe is first placed at the level of the cricoid cartilage in the transverse orientation. Once the cricoid cartilage is identified, the probe is then rotated 90 degrees counterclockwise, so the airway is visualized in the longitudinal axis (Fig. 7). The tracheal rings will be visualized as a series of hypoechoic structures anterior to a white, hyperechoic line, described as a "string of pearls" (Fig. 8). The transducer is moved cephalad to identify the thyroid cartilage. Once the cricothyroid membrane is identified in the longitudinal axis, insert a linear, metallic object such as a straightened paper clip or needle under the probe to create a shadow over the membrane. Remove the probe and use a skin marker to mark the area under the needle or paper clip [86]. This can also be performed dynamically, wherein the linear probe is slid just lateral to the midline. With the cricothyroid membrane in the center of the ultrasound screen, a horizontal incision is made through the membrane, just medial to the probe. The scalpel is rotated 90 degrees, the probe is released and a gum elastic bougie is inserted into the incision site. An ETT is then inserted into the trachea over the bougie. This technique was successful in 20 of 21 cadavers with a median time to insertion of 26 s [95].

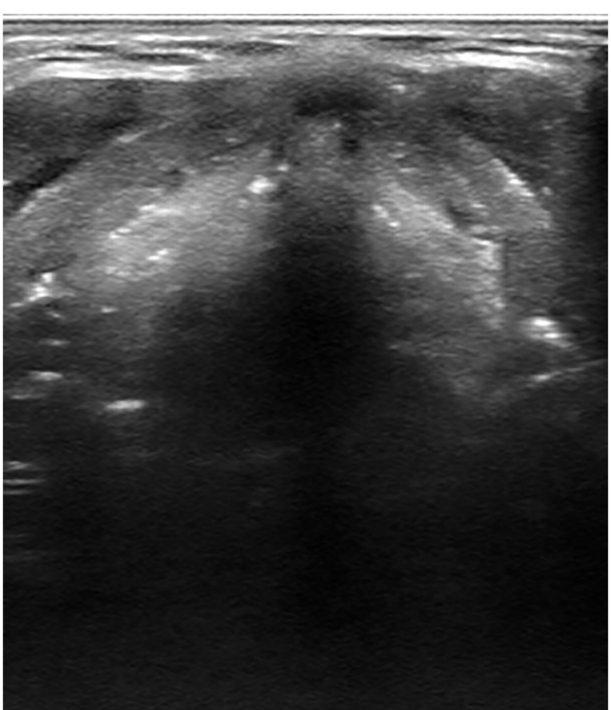

Fig. 5. Sonographic appearance of the thyroid cartilage.

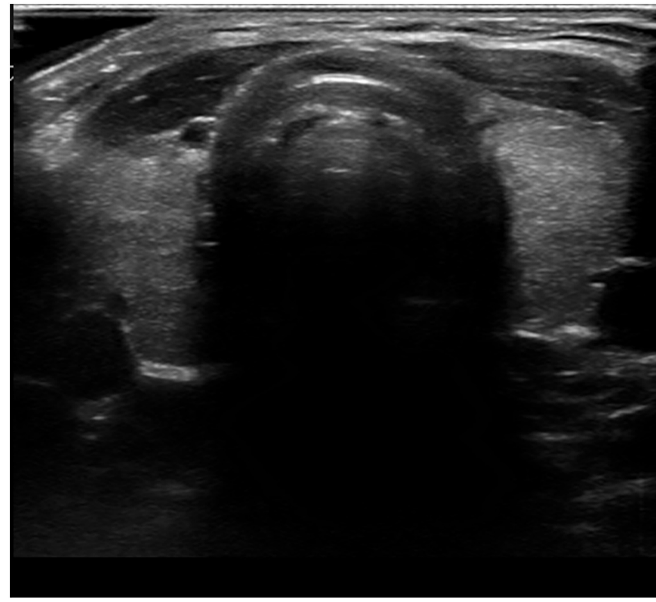

Fig. 6. Sonographic appearance of the cricoid cartilage.

Proponents of the static, pre-intubation technique favor this method because it removes the step of identifying the cricothyroid membrane during a time-sensitive procedure. Interestingly, a study of healthy, live volunteers showed only a 1 mm difference between the cricothyroid membrane location identified by ultrasound before and after simulated failed intubation, suggesting pre-marking the area prior to the intubation attempt may be reasonable and could be performed during pre-oxygenation [96].

As studies suggest EM physicians are able to rapidly identify the cricothyroid membrane with ultrasound, it seems reasonable to mark the cricothyroid membrane prior to intubation among patients with anticipated difficult airways [93,97]. If endotracheal intubation fails, the location for surgical cricothyroidotomy has already been marked, allowing the physician to proceed with minimal delay.

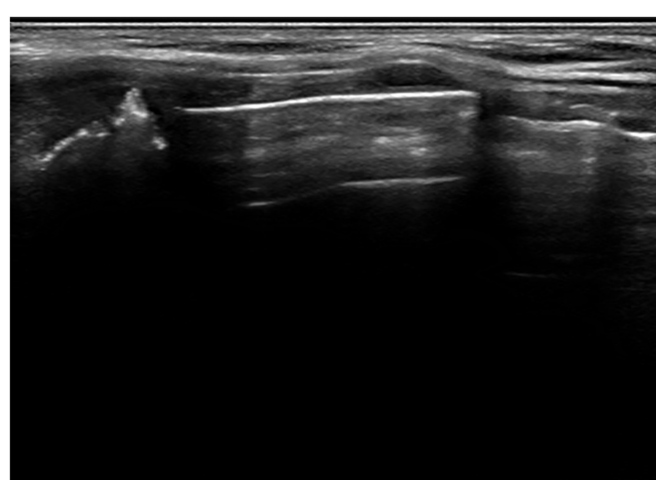

Fig. 7. Sonographic appearance of the cricothyroid membrane.

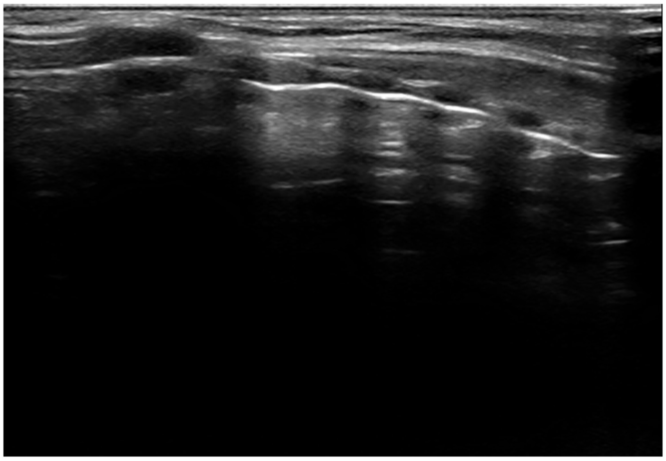

Fig. 8. Sonographic appearance of the tracheal rings.

7. Conclusion

Airway assessment and management is commonly performed in the ED setting. Because of the limitations with many of the traditional physical examination maneuvers, POCUS has been increasingly studied for the evaluation and management of the difficult airway. This article reviewed the current literature regarding the role of POCUS for airway assessment, intubation confirmation, ETT depth assessment, and performance of cricothyroidotomies.

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