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REVIEW ARTICLE/BRIEF REVIEW

Point-of-care ultrasound (POCUS) of the upper airway

Échographie au point d'intervention (PoCUS) des voies respiratoires supérieures

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Abstract *Airway management is a critical skill in the practice of several medical specialities including anesthesia, emergency medicine, and critical care. Over the years mounting evidence has showed an increasing role of ultrasound (US) in airway management. The objective of this narrative review is to provide an overview of the indications for point-of-care ultrasound (POCUS) of the upper airway. The use of US to guide and assist clinical airway management has potential benefits for both provider and patient. Ultrasound can be utilized to determine airway size and predict the appropriate diameter of single-lumen endotracheal tubes (ETTs), double-lumen ETTs, and tracheostomy tubes. Ultrasonography can differentiate tracheal, esophageal, and endobronchial intubation. Ultrasonography of the neck can accurately localize the cricothyroid membrane for emergency airway access and similarly identify tracheal rings for US-guided tracheostomy. In addition, US can identify vocal cord dysfunction and pathology before induction of anesthesia. A rapidly growing body of evidence showing ultrasonography used in conjunction with hands-on management of the airway may benefit patient care. Increasing awareness and use of POCUS for many indications have resulted in technologic advancements and increased accessibility and portability. Upper airway POCUS has the potential to become the first-line non-invasive adjunct assessment tool in airway management.*

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Résumé *La gestion des voies respiratoires constitue une compétence fondamentale pour plusieurs spécialités médicales, dont l'anesthésiologie, la médecine d'urgence et les soins intensifs. Au fil des ans, l'accumulation des données probantes a démontré le rôle de plus en plus important de l'échographie dans la gestion des voies aériennes. L'objectif de cette étude narrative est de fournir une vue d'ensemble des indications de l'échographie au point d'intervention des voies respiratoires supérieures. L'utilisation de l'échographie pour guider et aider la gestion clinique des voies aériennes présente des avantages potentiels pour le praticien et pour le patient. L'échographie peut servir à établir la taille des voies respiratoires et prédire le diamètre approprié des tubes endotrachéaux, des tubes à lumière double et des tubes de trachéotomie. Elle permet aussi de faire la différence entre intubation trachéale, œsophagienne et endobronchique. Au niveau du cou, elle peut localiser avec précision la membrane cricothyroïdienne pour un accès d'urgence aux voies respiratoires et identifier également les anneaux bronchiques pour une trachéotomie échoguidée. De plus, l'échographie peut identifier une atteinte des cordes vocales avant l'induction de l'anesthésie. Un ensemble rapidement croissant de données probantes montre que l'utilisation de l'échographie en association avec la gestion des voies aériennes peut être profitable pour les soins du patient. Une conscience et une utilisation accrues* *de l'échographie au point d'intervention ont abouti à des progrès technologiques, à une plus grande accessibilité et portabilité. L'échographie des voies aériennes supérieures au point d'intervention pourrait devenir l'outil d'évaluation non invasive de première intention dans la gestion des voies aériennes supérieures.*

The management of airways is a critical skill for anesthesiologists, as well as for other medical specialities including emergency medicine and critical care.[1,2] Airway mismanagement remains a major contributing factor to poor patient outcomes causing brain hypoxia and death.[1,2] Ultrasound (US), an imaging modality once reserved for radiologists, has been adopted by other medical disciplines. Anesthesiologists were among the early adopters of US in regional anesthesia and vascular access.[3] With improving technology and miniaturization of the US machine, accessibility and portability of US are now readily possible, allowing its use as a bedside tool for point-of-care US in airway management. While the airway consists of both the upper and lower airways, this narrative review on airway US will focus on the US of the upper airway. Therefore, the objectives of this narrative review are to provide an overview of how to obtain bedside real-time ultrasonography of the upper airway, how its use in clinical practice might be helpful in managing the airway, and the evidence-based clinical indications.

Case scenario

A 35-yr-old male patient presented in the emergency department with a self-inflicted gunshot wound to the mandible. The patient was sitting upright and maintaining an oxygen saturation in the high 80s. The airway mandible and oropharynx were grossly traumatized and bleeding heavily although distal airway structures were suggested in the back of the wound. With a trauma surgeon prepped and on standby, US of the upper airway was used to identify the cricothyroid membrane for potential front of neck access. The patient was successfully intubated awake with direct laryngoscopy and ultrasonography was used concomitantly to rule out esophageal or endobronchial intubation. The patient was urgently transferred to the operating room to obtain hemostasis and debride the wound.

The case scenario highlights the several roles of US in the management of the airway. In this narrative review we describe the indications of point-of-care of upper airway US in perioperative airway management.

Basic description of ultrasonography of the airway

Ultrasonography for airway management should be performed at the point of care by the airway manager as an adjunct to the desired procedures. A standard linear high-frequency transducer (13-6 MHz) is sufficient to scan the structures of the upper airway. The basic ultrasonographic appearance of the upper airway is shown in Figs. 1-4.

A strong echo (= a strong white line) will appear when the US beam reaches air.[4] This is the tissue-air border and everything beyond that line is only artefact. This means that we can depict the tissue from the skin to the anterior luminal surface of the upper airway from the mouth to mid-trachea.[5]

Ultrasonography for airway management, indications

Ultrasonography has a wide range of applications for safer airway management. The most important of the published indications are listed in the Table, which describes the use

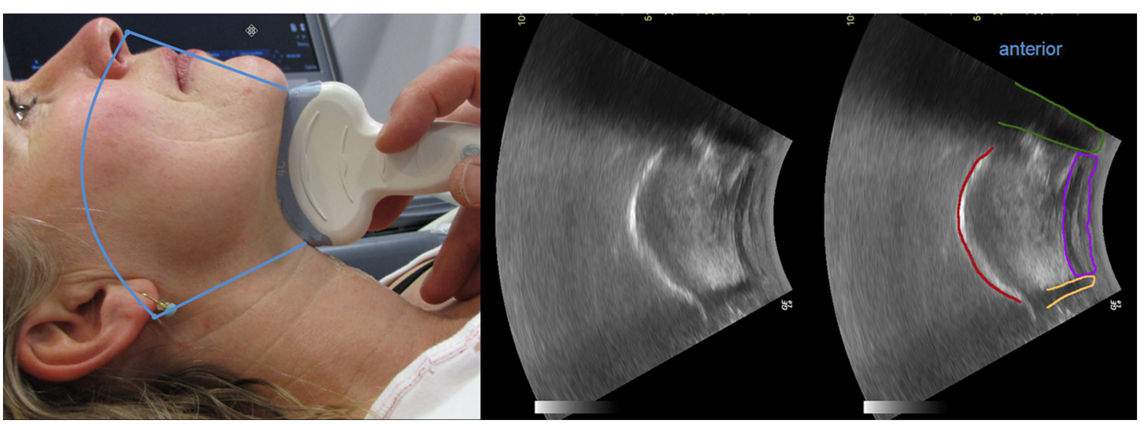

Fig. 1 Left: The curved, low-frequency transducer (5-2 MHz) and the area covered by the scanning (light blue). Middle: The resulting ultrasound image. Right: The shadow from the mentum of the mandible (green). The muscles in the floor of the mouth (purple). The shadow from the hyoid bone (light orange). The dorsal surface of the tongue (red). Reproduced with permission from: *Kristensen MS.* Ultrasonography in the management of the airway. Acta Anaesthesiol Scand 2011; 55: 1155-73[4]

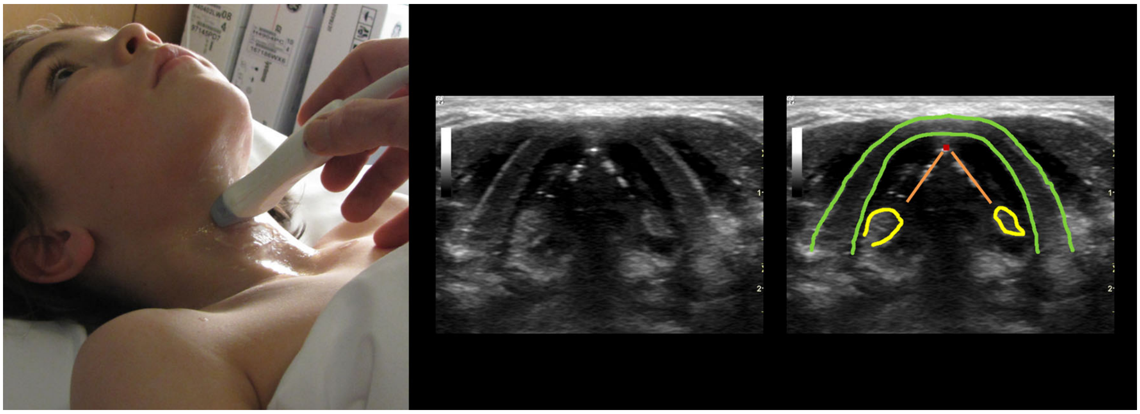

Fig. 2 Left: Transverse midline scan over the thyroid cartilage (in an eight-year-old boy). Thyroid cartilage (green). Vocal cords (orange). Anterior commissure (red). Arytenoid cartilages (yellow). Reproduced with permission from: *Kristensen MS.* Ultrasonography in the management of the airway. Acta Anaesthesiol Scand 2011; 55: 1155-73[4]

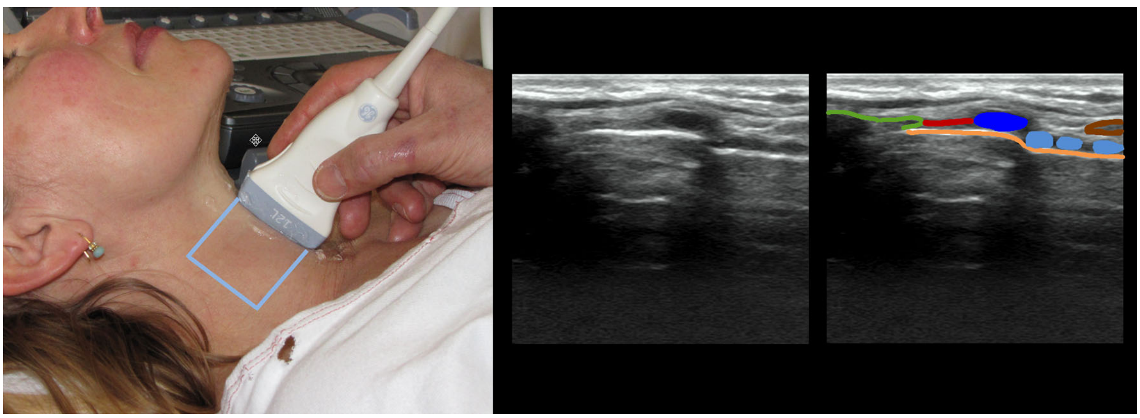

Fig. 3 Left: The linear high-frequency transducer (13-6 MHz) placed in the midsagittal plane; the scanning area is marked with light blue. Right: The thyroid cartilage (green). The cricoid cartilage (dark blue). Tracheal rings (light blue). The cricothyroid membrane (red). The tissue/air border (orange). The isthmus of the thyroid gland (brown). Below the orange line only artefacts are seen. Note the acoustic shadows below the cricoid and thyroid cartilages are due to calcification with increasing age. Reproduced with permission from: *Kristensen MS.* Ultrasonography in the management of the airway. Acta Anaesthesiol Scand 2011; 55: 1155-73[4]

of US in identifying the anatomical structures in the upper airway and its role in clinical applications. The evidence for all airway-related indications is beyond the scope of this narrative review, which focuses on the upper airway.

Localization of the cricothyroid membrane

The success rate of anesthesiologists attempting to perform lifesaving cricothyrotomy is unsatisfactorily low[17] although it is the ubiquitously recommended procedure[18,19] when ventilation and oxygenation with non-invasive methods fail. The inability to identify the cricothyroid membrane[20-23] by external visualization or palpation is an important contributor to this low success rate[17] and misplacement is the most common complication when attempting cricothyrotomy.[24] To improve the success rate of emergency cricothyrotomy, it has been recommended that the cricothyroid membrane be identified before induction of anesthesia[6,25] in all patients. If identification by inspection and/or palpation is not possible, then it can be performed with the help of US[4,5] as this greatly improves the rate of successful identification.[7,26] Additionally, US guidance reveals not only the location of the cricothyroid membrane but also the thickness of the tissue that has to be penetrated to gain access to the airway[5] and improves the success rate of cricothyrotomy in a study using human cadavers.[8]

Two techniques have been described for systematic, stepwise identification of the cricothyroid membrane: 1) the longitudinal "String of Pearls" (SOP) technique [5,27] and 2) the transverse "Thyroid-Airline-Cricoid-Airline" (TACA) technique.[27] The SOP technique[26] is the most well published and has proven its superiority over

Fig. 4 Transverse scan just cranial to the suprasternal notch and to the patient's left side of the trachea. Anterior part of tracheal cartilage (light blue) is visualized as C-shaped hypoechoic (cartilage) and hyperechoic (the tissue-air border) structures with shadowing. Esophagus (purple) is seen as a round structure to the left of the trachea without the hypo- and hyperechoic structures as seen in the trachea. Carotid artery (red) is a distinct round structure lateral to the trachea that is black because of absorption of sonographic waves by the blood. Reproduced with permission from: *Kristensen MS.* Ultrasonography in the management of the airway. Acta Anaesthesiol Scand 2011; 55: 1155-73[4]

Table Indications for airway ultrasound

Anatomical structure examined	Clinical indications	Type of study*
Cricothyroid membrane and trachea	Pre-anesthetic airway evaluation to be prepared for emergency front of neck airway access[6-8]	Randomized-controlled trial, prospective cohort, narrative review
	For elective tracheostomy[9] and other kinds of access to the airway via the anterior neck[1]	Randomized-controlled trial, prospective cohort
Tracheal placement of endotracheal tube	Evaluation of the placement of a breathing tube, in trachea, main-stem bronchus or esophagus[10,11]	Randomized-controlled trial, prospective cohort and observational, systematic review, meta-analysis
Trachea	Predicting the optimal size of endotracheal, double-lumen, and tracheostomy-tubes[12-14]	Randomized-controlled trial, prospective cohort and observational, case series
Vocal cords	Identification of vocal cord palsy and other pathology[15,16]	Prospective cohort and observational

*Types of studies describing each section's references listed in this narrative review

For certain indications not included in the Table, please refer to *Kristensen MS, Teoh WH, Graumann O, Laursen CB.* Ultrasonography for clinical decision-making and intervention in airway management: from the mouth to the lungs and pleurae. Insights Imaging 2014; 5: 253-79,[5] and to this video link: http://airwaymanagement.dk/171/index.php?option=com_content&view=category&layout=blog&id=12&Itemid=115

palpation in a cadaveric study that showed its ability to heighten success and limit tube misplacement in cricothyrotomy.[8] Furthermore, this same technique can be used to identify the optimal interspace between tracheal rings for placement of a tracheostomy tube. We recommend the longitudinal technique as the first to learn and as the initial technique, such that every anesthesia department dealing with difficult airways on a regular basis should have the expertise to apply it. For patients with a very short neck, or flexion-deformity of the neck that leaves no space to place the US transducer in the longitudinal position, we recommend the transverse TACA technique to identify the cricothyroid membrane, as in these subsets of patients, this may be the only successful technique.[27] Achieving a hundred percent success rate of identifying the cricothyroid membrane is possible when the longitudinal SOP technique is applied in tandem with the transverse TACA technique.[27]

Performing the longitudinal "SOP" technique (String of Pearls):[27]

1) The sternal bone is identified and the transducer is placed transversely on the patient's neck just cephalad to the suprasternal notch to visualize the trachea (horseshoe-shaped dark structure with a posterior white line) (Fig. 5, first row).

2) The transducer is slid towards the patient's right side (towards the operator) so that the right border of the transducer is positioned midline of the trachea and the US image of the tracheal ring is thus truncated into half on the screen (Fig. 5, second row).

3) The right end of the transducer is maintained over the midline of the trachea, while the left end is rotated 90° into

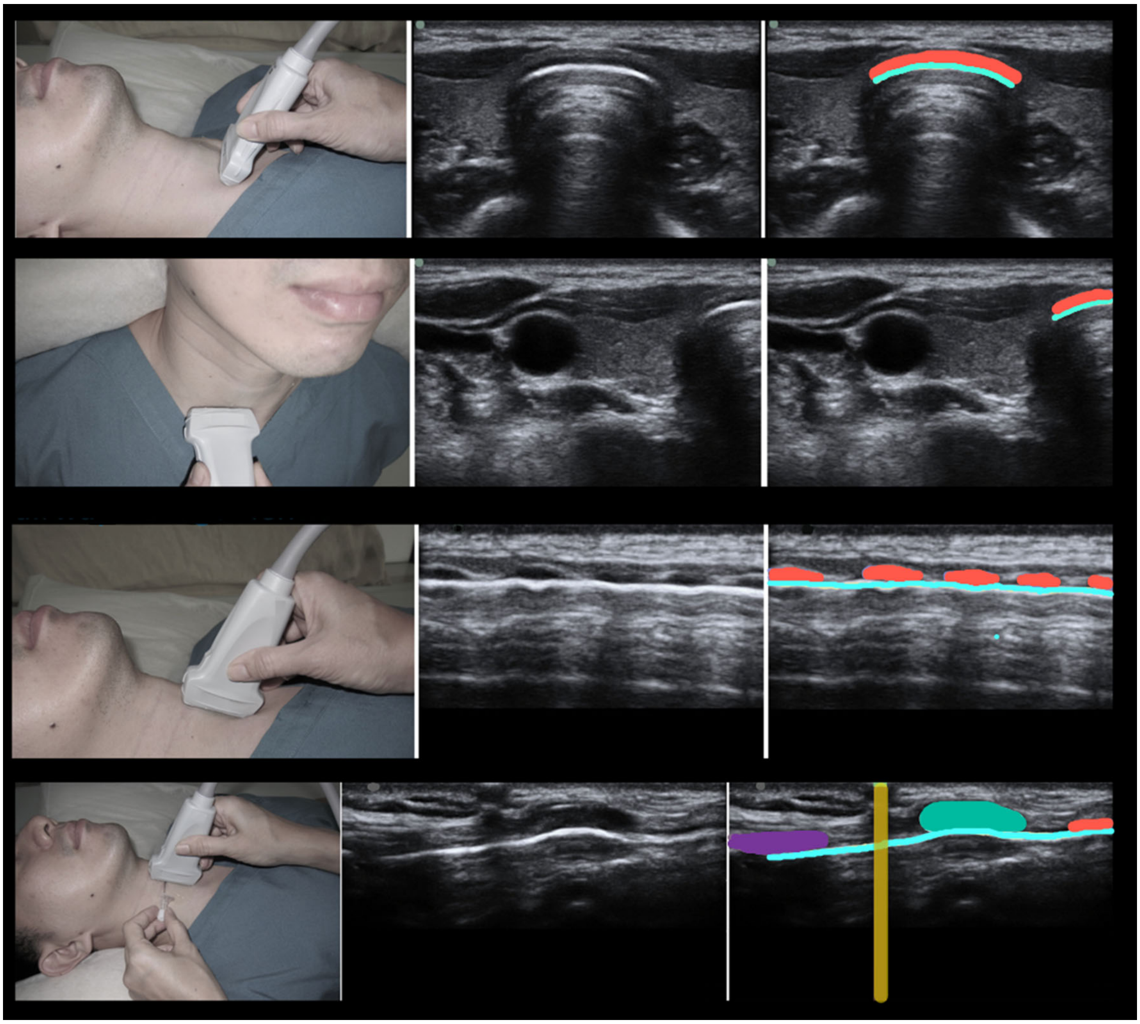

Fig. 5 The longitudinal "String of Pearls" (SOP) technique for identifying the cricothyroid membrane and the interspaces between tracheal rings. See the text for details. Orange-red = tracheal ring; light blue = the tissue-air border; green = the cricoid cartilage; purple = the distal end of the thyroid cartilage. Yellow = the shadow from the needle slid in between the transducer and the skin. With permission from The Scandinavian Airway Management course "www.airwaymanagement.dk"

the sagittal plane resulting in a longitudinal scan of the midline of the trachea. A number of dark (hypoechoic) rings will be seen anterior to the white hyperechoic line (air-tissue border), akin to a "string of pearls". The dark hypoechoic "pearls" are the anterior part of the tracheal rings (Fig. 5, third row).

4) The transducer is kept longitudinally in the midline and slid cephalad until the cricoid cartilage comes into view (seen as a larger, more elongated and anteriorly placed dark "pearl" compared with the other tracheal rings). Further cephalad, the distal part of the thyroid cartilage can be seen as well (Fig. 5, fourth row). The longitudinal course of the midline of the airway can be marked with a pen.

5) While still holding the transducer, the other hand is used to slide a needle (as a marker, for its ability to cast a shadow in the US image) between the transducer and the patient's skin until the needle's shadow is seen midway between the caudal border of the thyroid cartilage and the cephalad border of the cricoid cartilage (Fig. 5, fourth row).

6) Now the transducer is removed and the needle marks the centre of the cricothyroid membrane in the transverse plane. This can be marked on the skin with a pen.

The technique is shown in this video: http://airwaymanagement.dk/pearls.[28]

Performing the Transverse "TACA" technique (Thyroid cartilage, Airline, Cricoid cartilage, Airline):[27]

1) Estimate the thyroid cartilage's level on the neck and place the US transducer transversely over it, scanning to identify the thyroid cartilage as a hyperechoic triangular structure (Fig. 6, first row).

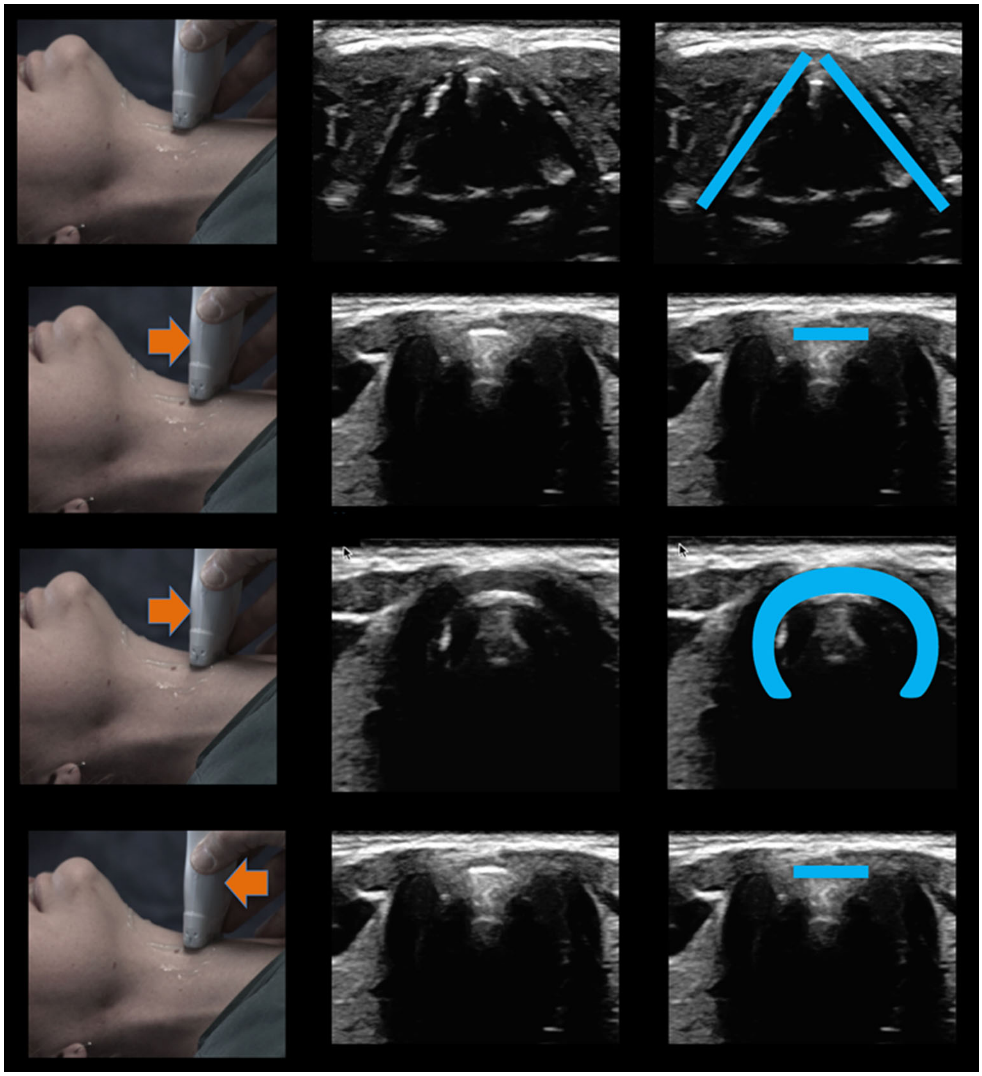

Fig. 6 The transverse "thyroid-airline-cricoid-airline" (TACA) technique for identifying the cricothyroid membrane. See the text for details. Blue triangle = thyroid cartilage; blue horizontal line = the "airline" = the cricothyroid membrane; blue "lying C" = the anterior part of the cricoid cartilage. With permission from The Scandinavian Airway Management course " www.airwaymanagement.dk"

2) Move the transducer caudally until the cricothyroid membrane is identified: this is recognizable as a hyperechoic white line resulting from the echo of the air-tissue border of the mucosal lining on the inside of the cricothyroid membrane, often with parallel white lines (reverberation artefacts) below (Fig. 6, second row).

3) Move the transducer further caudally until the cricoid cartilage is identified (a black "lying C" with a white lining) (Fig. 6, third row).

4) Finally, move the transducer slightly back cephalad until the centre of the cricothyroid membrane is identified (Fig. 6, fourth row).

5) The centre can be marked both transversely and sagittally on the skin with a pen. By identifying the highly characteristic shapes of both the thyroid and cricoid cartilages, both the cephalad and caudal borders of the cricothyroid membrane can be identified.

The technique is shown in this video: http://airwaymanagement.dk/taca.[29]

In conclusion, US-guided localization of the cricothyroid membrane fills the void of very poor results of accurate localization by visualization or palpation. It is easily learned and should be considered, if not routinely, then at least before embarking on management of anticipated difficult airway situations.

Confirmation of tracheal intubation

The use of US for confirmation of endotracheal tube placement has gained increasing popularity as an adjunct to

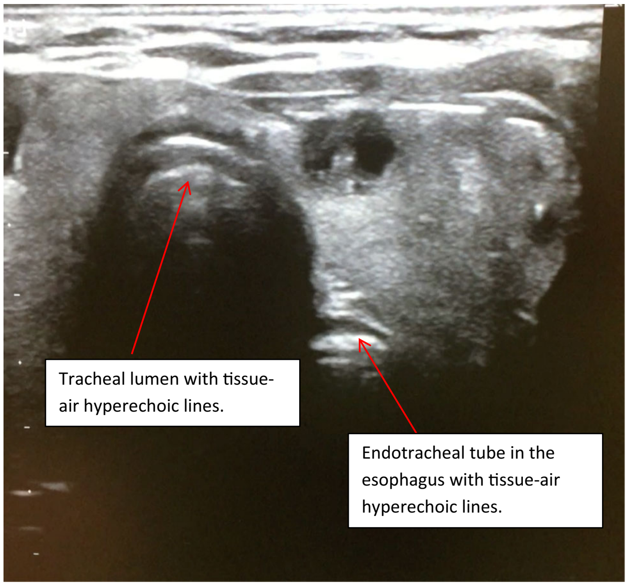

Fig. 7 Esophageal intubation. Transverse scan just cranial to the suprasternal notch and to the left side of the patient's trachea. An esophageal intubation is shown as an adjacent hyperechoic structure with shadowing posterolateral to the trachea, consistent with the endotracheal tube within the esophagus. The tissue-air hyperechoic lines are visualized in the trachea and esophagus (because of esophageal intubation); this has been referred to as the *"double tract sign"*[39]

standards of practice, including end-tidal CO_2, visualization of the tube between cords, and endoscopic visualization of tracheal rings through the endotracheal tube (ETT). Currently, several prospective studies and systematic reviews show the accuracy of US in confirming the correct placement of the ETT by excluding esophageal intubation.[10,11,30] In a systematic review and meta-analysis, Chou *et al.* studied the diagnostic accuracy of using tracheal US to examine ETT placement during emergency intubations by indirectly excluding esophageal intubation.[10] A total of 12 eligible studies involving adult patients and cadaveric models were identified. For detection of esophageal intubation, the pooled sensitivity was 0.93 (95% confidence interval [CI], 0.86 to 0.96) and the specificity was 0.97 (95% CI, 0.95 to 0.98).

Several prospective studies on human and cadaveric models evaluated the sensitivity and specificity of US confirmation of tube placement in the trachea.[30-38] In a meta-analysis of 969 intubations performed in emergency and elective situations, Das *et al.* showed that transtracheal ultrasonography's pooled sensitivity and specificity were 0.98 (95% CI, 0.97 to 0.99) and 0.98 (95% CI, 0.95 to 0.99), respectively.[11] In emergency scenarios, transtracheal US showed an aggregate sensitivity and specificity of 0.98 (95% CI, 0.97 to 0.99) and 0.94 (95% CI, 0.86 to 0.98), respectively.

Various US techniques have been used to visualize diaphragmatic movements, lung sliding, methods, and transtracheal identification of correct tube placement in the trachea and its distinction from endobronchial intubation.[31-34] At present, there is a lack of data comparing the accuracy of different US techniques. Regardless of the technique chosen, US can be used to evaluate proper ETT placement in the trachea by indirectly ruling out an esophageal intubation.

Technique for confirmation of tracheal intubation with ultrasonography

In the section below we explain the most consistently described US technique for excluding esophageal placement of the endotracheal tube. A curved US probe may be used; however, tracheal rings are superficial and we recommend using a high-frequency linear probe. If time permits, one should visualize the normal airway anatomy before placing the ETT (Fig. 1).

The US probe should be placed above the suprasternal notch in a transverse direction. At this point, caution should be exercised not to apply too much pressure as this may distort the airway anatomy. As described earlier, on ultrasonography a tracheal ring is visualized as C-shaped hypoechoic (cartilage) and hyperechoic structures (the tissue-air border) with shadowing (Fig. 4). The esophagus is usually seen on one side of the trachea as an oval structure with a hyperechoic wall and hypoechoic centre (Fig. 4). Tracheal US can be performed in real time as the ETT is passed. An esophageal intubation will reveal an adjacent hyperechoic structure with shadowing posterolateral to the trachea, consistent with the ETT location within the esophagus. This has been referred to as the "double tract sign"[39] (Fig. 7). It should be noted that if the esophagus is located directly posterior to the trachea, an esophageal intubation may be missed by US as this second hyperechoic structure will be obscured by the shadowing from the trachea.

Current research suggests the use of focused US is feasible to rapidly confirm tracheal or esophageal placement of ETTs. Large prospective studies are needed to investigate the learning curve of this technique by novice operators before recommending its routine use in anesthesia practice.

Tracheostomy

Ultrasonography is a useful adjunct for both surgical and dilatational tracheostomy as it may increase the success rate by helping to identify the trachea and the optimal interspace between tracheal rings, determine the depth to the tracheal lumen, and identify overlaying blood vessels or other pathology prior to the procedure. Knowledge of these factors may inform the decision whether to offer a surgical or a dilatational tracheostomy. Ultrasonography can be applied 1) before the procedure itself either to guide the decision as to whether the best approach is a surgical one in case of overlying large blood vessels, inability to identify an appropriate interspace between the tracheal rings, typically in very short necks, and subcutaneous emphysema or a dilatational technique or to prepare for the dilatational technique,[9,40] 2) before and during the procedure instead of guidance by a flexible bronchoscope, or 3) in combination with a flexible bronchoscope.

Identifying the trachea can be challenging in obese patients; those with a short thick neck, neck mass, previous surgery, or radiotherapy to the neck; thoracic pathology; or other conditions resulting in tracheal deviation.[41] Even the addition of chest radiography and techniques of needle aspiration to locate the trachea may be futile.[42] Under such circumstances, preoperative US for localization of the trachea and the tracheal structures is extremely useful.[42] Pre-procedural US often leads to a change in technique from dilatational to surgical or the inverse[9] and to a change in the selection of the best interspace between the tracheal rings.[43]

Following pre-procedural US scanning and marking of appropriate interspace between tracheal rings, the tracheostomy itself can be performed solely with clinical guidance,[9] with US guidance, or with flexible bronchoscopy. Of these, only the flexible bronchoscope allows intraluminal observation of the needle and guidewire in the trachea; whereas only US allows real-time measurement of the skin depth to the tracheal wall, both measures prevent penetration of the posterior tracheal wall. Occasionally, the obstruction of the lumen of the airway caused by the flexible scope may interfere with adequate ventilation and oxygenation of the patient; this can be avoided by using a US-only technique.[43,44]

When comparing a landmark technique with the real-time out-of-plane US-guided transverse technique, the latter revealed a higher first-pass success (87% *vs* 58 %) and less deviation from the midline with the US-guided technique.[45] The study included bronchoscopy during the dilatational part of the procedure. When comparing US with bronchoscopy guidance, Gobatto *et al*. found a 5% rate of puncture of the orotracheal tube in the US group *vs* 1.7 % in the bronchoscopy group (P = 0.619) but concluded that overall US guidance is an acceptable alternative to bronchoscopy guidance.[46]

Real-time US guidance with visualization of the needle path by means of a linear high-frequency transducer placed transversely over the trachea was successful in a feasibility study of 13 patients.[47] Nevertheless, the real-time US guidance of the procedure has a fairly long learning curve. In a study of 85 consecutive patients, it was found that 20 procedures had to be performed before obtaining a low frequency of major complications; a proficiency of 50 procedures is required before the combination of procedure time and overall complication rate is fully satisfactory.[48]

We recommend a routine pre-emptive US examination to determine if a dilatational or surgical tracheostomy is most suited for the patient and to choose the ideal entry site. This technique is easily learned. The information obtained regarding the position of the ideal tracheal interspace, the distance from the skin to luminal air, and overlying blood vessels to avoid is then used to mark the possible entry sites and guide the subsequent tracheostomy. If the US examiner is experienced, US can be continued in real time during needle insertion. Ideally, both US and procedural flexible bronchoscopy are used in combination—as this will add the possibility to observe the needle entry into the tracheal lumen to avoid penetration of the posterior wall, as a supplement to the advantages obtained with US.

Tracheal diameter and appropriate sizing of endotracheal and tracheostomy tubes

Ultrasound is a reliable tool for assessment of the subglottic upper airway diameter and is validated against magnetic resonance imaging[49] and computed tomography scans.[14] In the pediatric population the subglottic transverse diameter measured by US correlates well with the endotracheal tube outer diameter and is superior to age- and height-based formulas in estimating endotracheal tube size.[12,50,51] Moreover, US can predict the proper tracheostomy tube size for exchange in children by assessing the internal and external transverse tracheal diameter and the depth of the trachea from the skin surface.[13] In this small series of four children, US confirmed that a new larger fenestrated tracheostomy tube could be replaced in one child but not in the other three children because of lack of space to allow for a larger tracheostomy tube.[13]

The diameter of the left mainstem bronchus, and thus the proper size of a left-sided double-lumen ETT, can be estimated by measuring the outer tracheal width with the US probe placed in the transverse position just above the sternoclavicular joint.[14,52] In a series of 45 patients undergoing intubation with a left-sided double-lumen ETT, Sustic *et al.* showed a strong correlation between tracheal width as measured by US and tracheal width (r = 0.882) and left main bronchus width (r = 0.832) as measured by computed tomography.[14] Furthermore, US was shown to be superior to conventional clinical assessment for predicting the correct size of left-sided double-lumen ETT.[52]

Ultrasound is superior to conventional clinical assessment for predicting the appropriate size of single-lumen ETTs, double-lumen ETTs, and tracheostomy tubes in pediatric and adult populations.

The vocal cords

The vocal cords are composed of mucous membrane infoldings attached anteriorly at the angle on the interior surface of the thyroid cartilage and project posteriorly to the arytenoid cartilages on either side.[53] Based on the anatomy, the vocal cords are best seen with the US transducer placed in the transverse position over the thyroid cartilage. At this location, the true and false vocal cords can be seen by moving the transducer in a cephalocaudad direction over the thyroid cartilage.[54] The true vocal cords appear as two triangular hypoechoic structures (the vocalis muscles), outlined medially by the hyperechoic vocal ligaments (Fig. 2 orange lines), and oscillate and move toward the midline during phonation.[54]

Ultrasonography of the vocal cord movement has been reported for the assessment of superior laryngeal nerve or recurrent laryngeal nerve injuries after neck surgeries.[55,56] Translaryngeal US can identify a high proportion of lesions on the vocal cords such as cysts, polyps, and papillomatosis in pediatric patients.[57] Nevertheless, successful visualization of the true vocal cords is significantly lower than that of the false vocal cords or arytenoids.[15] In a study on 229 participants with variable ages from two months to 81 yr, the true and false cords were visible in all female participants.[15] In males, the visibility was 100% below the age of 18 and gradually decreased to $< 40\%$ of males ≤ 60 yr.[58] In addition, the success rate of true cord visualization with US is reduced with calcification of the thyroid cartilage.[59] In a prospective study of 529 patients scheduled for thyroid or parathyroid surgeries, preoperative ultrasonography was successful as a screening tool to evaluate vocal cord movement in 84% of the patients and directing those with vocal cord abnormalities for invasive flexible bronchoscopy.[16]

Ultrasound can visualize true cord movement in females of all ages, but visualization is reduced in males with increasing age and in patients with calcified thyroid cartilage. Laryngeal US can accurately screen patients and direct patients who have a higher pretest probability of vocal cord dysfunction for flexible bronchoscopy. For the pediatric population in whom anesthesia may be required for flexible bronchoscopy to assess vocal cord functions, US has the advantages of being pain free, non-invasive, and without the need of anesthesia.

Diaphragm functions

While not the upper airway per se, we briefly summarize the evidence on the use of diaphragm US to measure "diaphragm excursion" and the "thickening fraction" to predict weaning success/failure of mechanically ventilated patients, particularly in the intensive care units.[60-63] The detailed description of these measures is beyond the scope of this review but has been described elsewere.[64-67] Two studies[60,61] comparing diaphragm excursion with the traditional weaning index found the sensitivity of diaphragm excursion to be 84.4 and 60% and specificity of 82.6 and 76%, respectively. Thickening of the diaphragm and thickening fraction is another measure used by DiNino *et al.*[68] and Ferrari *et al.*[69] against traditional measurement of the rapid shallow breathing index. They found the sensitivity of this measure to be as high as 88 and 82% and specificity of 71% and 88%, respectively.

Diaphragm US can be a useful and accurate tool to predict the success or failure of extubation in the critical care patient population.

Resolution of the case scenario

After several days of mechanical ventilation in the intensive care unit, the patient required tracheostomy for ongoing airway protection. A pre-procedural US examination was used to determine if a dilatational or a surgical tracheostomy was most suited for the patient and to choose the ideal entry site. Several weeks later, after being discharged from the hospital, the patient returned to clinic where laryngeal US was again used to assess vocal cord function in preparation for decannulation of the tracheostomy tube.

Training in upper airway US

Although there is currently no standardized training in upper airway US,[70] limited studies suggest relatively short duration of training is sufficient to learn certain skills.[71,72] Cumulative sum analysis of learning curves showed that anesthesia trainees achieved competence, defined as a 90% success rate, in US identification of the cricothyroid membrane in a series of 20 US scans, after a short two-hour training session with fewer than 20 scans in a mean time less than 60 sec, and that they remained reasonably competent three months later.[71] Following a brief 20-min didactic teaching and a 30-min practice session on upper airway US, emergency medicine fellows lacking formal airway bedside US training were able to identify the location and depth of a saline-filled endotracheal tube above or at the suprasternal notch in an adult cadaver model with a sensitivity of 96 % (23 of 24).[72] These studies suggest the training required for US identification of the cricothyroid membrane and endotracheal tube seems to be short even without prior airway US experience. The number of supervised US examinations required to maintain competence is debatable. Using the Objective Structured Assessment of Ultrasound Skills is a valid and reliable method[68,69] that might also be valuable to assess basic ultrasonography of the upper airway and may help determine when trainees are qualified for independent practice. Our recommendation is a minimum of 25 supervised US scans for each procedure or outcome. It is particularly important to train in POCUS for cricothyroid membrane identification, where existing modalities are unreliable for the purpose, in contrast to other applications, where POCUS is an additional option alongside existing fairly reliable modalities. Further research regarding training education in upper airway US is warranted.

Future directions

Upper airway US is useful in airway management because of its portability, minimal invasiveness, cost effectiveness, low radiation exposure, and accessibility. Modern advancements in ultrasonography technologies such as three-dimensional US may be useful in the complex evaluation of upper and lower airway anatomy with accurate prediction of difficult airways, diagnosis of obstructive sleep apnea, and guidance of airway nerve blocks.

Conclusions

Ultrasound has many advantages for imaging the upper airway; it is safe, quick, portable, and accessible and provides static and real-time dynamic images relevant for various clinical indications of management of the airway. Upper airway POCUS can be used dynamically for optimal benefit in perioperative airway management, immediately before, during, and after airway interventions. Acute airway procedures under real-time US guidance may become standard procedures in anesthesia, emergency, and intensive care settings. With a growing body of evidence in many clinical applications, there is a need to incorporate upper airway US education and training of personnel responsible for perioperative airway management. POCUS of the upper airway has the potential to become a first-line non-invasive airway assessment tool.

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