Review Article

Ultrasonography in the management of the airway

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In this study, it is described how to use ultrasonography (US) for real-time imaging of the airway from the mouth, over pharynx, larynx, and trachea to the peripheral alveoli, and how to use this in airway management. US has several advantages for imaging of the airway – it is safe, quick, repeatable, portable, widely available, and it must be used *dynamically* for maximum benefit in airway management, in direct conjunction with the airway management, i.e. immediately before, during, and after airway interventions. US can be used for direct observation of whether the tube enters the trachea or the esophagus by placing the ultrasound probe transversely on the neck at the level of the suprasternal notch during intubation, thus confirming intubation *without* the need for ventilation or circulation. US can be applied before anesthesia induction and diagnose several conditions that affect airway management, but it remains to be determined in which kind of patients the predictive value of such an examination is high enough to recommend this as a routine approach to airway management planning. US can identify the croicothyroid membrane prior to management of a difficult airway, can confirm ventilation by observing lung sliding bilaterally and should be the first diagnostic approach when a pneumothorax is suspected intraoperatively or during initial trauma-evaluation. US can improve percutaneous dilatational tracheostomy by identifying the correct tracheal-ring interspace, avoiding blood vessels and determining the depth from the skin to the tracheal wall.

MANAGEMENT of the airway remains a major contributor to death and brain damage in anesthesia, emergency medicine, and intensive care settings.[1,2] The purpose of this review was to give an overview of how to obtain bedside real-time ultrasonographic images of the upper and lower airway, and how to use this in clinical praxis in improving the management of the airway. The target groups are anesthesiologists and emergency and intensive care unit (ICU) doctors involved in airway management.

Methods

This is a narrative review combined with a structured Medline literature search. The following search terms were used:

A) (ultrasound OR ultrasonic OR ultrasonography OR ultrasonographically OR sonography OR ultrasonographic) AND (vocal cords OR vocal folds OR subglottic OR epiglottis OR extubation OR cricothyrotomy OR tracheostomy OR airway OR larynx OR laryngeal OR laryngoscopy OR endotracheal tube OR endotracheal intubation OR tracheal intubation OR esophageal intubation OR laryngeal mask airway OR ventilation OR nasogastric OR gastric tube),

B) (ultrasound OR ultrasonic OR ultrasonography OR ultrasonographically OR sonography OR ultrasonographic) AND (Pneumothorax or lung).

The reference list of the retrieved articles were additionally scrutinized for relevance.

Introduction

Ultrasonography (US) has many potential advantages – it is safe, quick, repeatable, portable, widely available, and gives real-time dynamic images. US must be used *dynamically* in direct conjunction with the airway procedures for maximum benefit in airway management. For example, if you place the transducer on the neck, you can see if the tube passes to the trachea or to the esophagus *while* it is being placed, whereas you are unlikely to see the location of the tube if you place the transducer on the neck of a patient who already has an endotracheal tube in place.

The ultrasound image and how to obtain it

Ultrasound refers to sound beyond 20,000 Hz and frequencies from 2 MHz to 15 MHz are normally used for medical imaging. Ultrasound transducers act as both transmitters and receivers of reflected sound. Tissues exhibit differing acoustic impedance, and sound reflection occurs at interfaces between different types of tissues. The impedance difference is greatest at interfaces of soft tissues with bone or air. Some tissues give a strong echo (fat and bone, for example); these structures are called *hyperechoic* structures and appear *white*. Other tissues let the ultrasound beam pass easily (fluid collections or blood in vessels, for example), and thus create only little echo; they are called *hypoechoic* and appear *black* on the screen. When the ultrasound beam reaches the surface of a bone, a strong echo (a strong white line) appears and there is a strong absorption of ultrasound resulting in a limited depth of the bony tissue being depicted. Nothing is seen beyond the bone because of acoustic shadowing. Cartilaginous structures, such as the thyroid cartilage, the cricoid cartilage and the tracheal rings, appear homogeneously hypoechoic[3] (black), but the cartilages tends to calcify with age. Muscles and connective tissue membranes are hypoechoic but have a more heterogeneous striated appearance then cartilage.[3] Glandular structures such as the submandibular and thyroid glands are homogeneous and mildly to strongly hyperechoic in comparison with adjacent soft tissues. Air is a very weak conductor of ultrasound so when the ultrasound beam reaches the tissue/air border, a strong reflection (a strong white line) appears and everything on the screen beyond that point are only artifacts, especially reverberation artifacts that creates multiple parallel white lines on the screen. However, the artifacts that arise from the pleura/lung border often reveal useful information. Visualization of structures such as the posterior pharynx, posterior commissure, and posterior wall of the trachea is thus prevented by intraluminal air.[3] In B-mode US, an array of transducers simultaneously scans a plane through the body that can be viewed as a 2-D image on screen, depicting a "slice of tissue".

In M-mode (M = motion), a rapid sequence of B-mode scans, representing one single line through the tissue, whose images follow each other in sequence on screen, enables us to see and measure range of motion, as the organ boundaries that produce reflections move relative to the probe.

When using Color Doppler velocity information is presented as a color-coded overlay on top of a B-mode image. It is characteristic for ultrasound that the higher the frequency of the ultrasound wave, the higher the image resolution is and the lesser the penetration in depth. All modern US transducers used in airway management have a range of frequencies that can be adjusted during scanning in order to optimize the image. The linear high-frequency transducer (Fig. 1) is the most suitable for

Fig. 1. Laptop-sized ultrasonography machine with transducers. Left: Linear 7–12 MHz high-frequency transducer. Second from left: Small, linear 6–10 MHz high-frequency "hockey stick" transducer. Upper right: Curved, Convex 2–6 MHz low-frequency transducer. Foreground, insert, micro convex 4–10-MHz transducer.
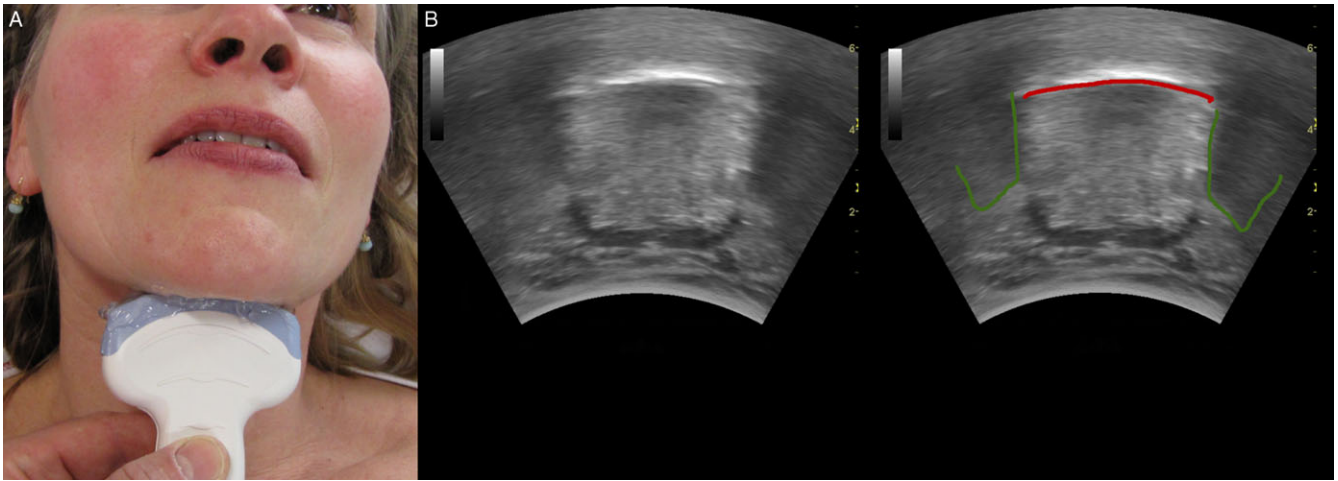
Fig. 2. (A) Transverse scan of the floor of the mouth and the tongue.(B) Dorsal surface of the tongue (red). Shades arising from the mandible (green).

imaging superficial airway structures (within 2–3 cm from the skin).[3] The curved low-frequency transducer is most suitable for obtaining sagittal and parasagittal views of structures in the submandibular and supraglottic regions, mainly because of its wider field of view. The micro convex transducer gives a wide view of the pleura between two ribs. If you must choose to use only one transducer, then a linear high-frequency transducer will enable you to perform the majority of ultrasound examinations relevant for airway management. Because the air does not conduct ultrasound, the probe must be in full contact with the skin[4] or mucosa without any interfacing air. This is obtained by applying judicious amounts of conductive gel between the probe and the skin. Because of the prominent thyroid cartilage in the male, it is sometimes a challenge to avoid air under the probe when performing a sagittal midline scan from the hyoid bone to the suprasternal notch. Portable machines can provide accurate answers to basic questions[5] and are thus sufficient for airway US.

Visualizing the airway and the adjacent structures

With conventional transcutaneous US we can visualize the airway from the tip of the chin to the mid-trachea plus the pleural aspect of the most peripheral alveoli as well as the diaphragm. Additional parts of the airway can be seen with special techniques: Trachea can be seen from the esophagus when performing transesophageal US and the tissue surrounding the more distal airway from the mid-

trachea to the bronchi can be visualized with endoscopic US via a bronchoscope. These special techniques will not be covered in detail in this article.

Mouth and tongue

US is a simple method for examination of the mouth[6] and its content. The tongue can be visualized from within the mouth[7] but the image can be difficult to interpret.[8] If the transducer is placed in the coronal plane just posterior to the mentum and from there moved posteriorly until the hyoid bone is reached, it will allow a thorough evaluation of all the layers of the floor of the mouth, of the muscles of the tongue, and of possible pathological processes (Fig. 2). The scanning image will be flanked by the acoustic shadow of the mandible on each side. The dorsal lingual surface is clearly identified.[9] The width of the tongue base can be measured in a standardized way by localizing the two lingual arteries with Doppler and subsequently measuring the distance between these arteries where they enter the tongue base at its lower lateral borders.[10] A longitudinal scan of the floor of the mouth and the tongue is obtained if the transducer is placed submentally in the sagittal plane and the whole length of the floor of the mouth and the majority of the length of the tongue can be seen in one image (Fig. 3). The acoustic shadows from the symphysis of the mandible and from the hyoid bone form the anterior and posterior limits of this image. Detailed imaging of the function of the tongue can be evaluated in this plane.[9] When the tongue is in contact with the palate, then the palate can be visualized;
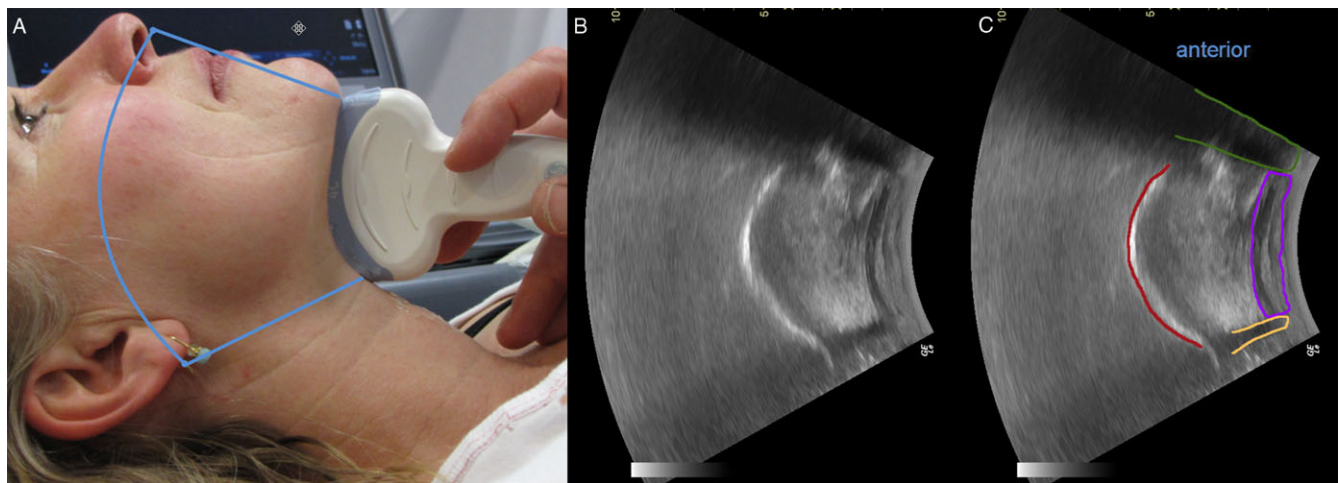
Fig. 3. (A) *The curved, low-frequency transducer and the area covered by the scanning (light blue).* (B) *The resulting ultrasound image.* (C) *The shadow from the mentum of the mandible (green). The muscles in the floor of the mouth (purple). The shadow from the hyoid bone (light orange). The dorsal surface of the tongue (red).*
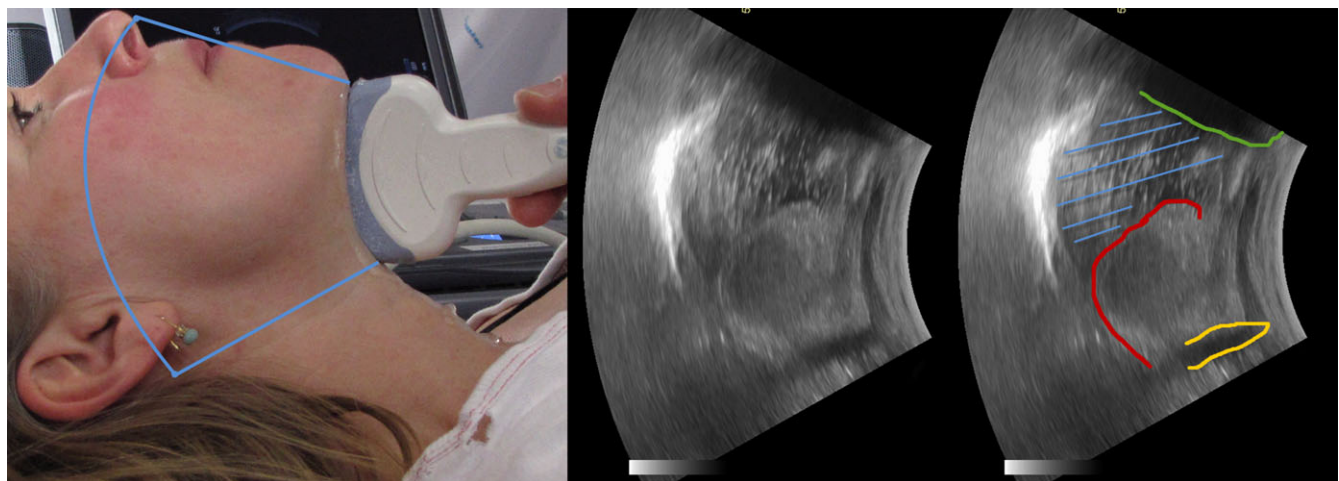

Fig. 4. The tongue and the mouth filled with water. The shadow from the mentum of the mandible (green). The shadow from the hyoid bone (light orange). The dorsal surface of the tongue (red). The water in the mouth (blue lines). The large white line represents the strong echo from the hard palate.

when there is no contact with the palate, the air at the dorsum of the tongue will make visualization of the palate impossible. An improved image is achievable if water is ingested and retained in the oral cavity allowing (Fig. 4) a better differentiation of the hard palate from the soft palate.[6] The tongue can be visualized in detail using 3-D US.[11] In the child, the major anatomical components of the tongue and the mouth are covered by four scanning positions: the midline sagittal, the parasagittal, the anterior coronal, and the posterior coronal plane.[12] In the transverse midline plane just cranial to the hyoid bone, the tongue base and the floor of the mouth is

seen. In the transverse (axial) plane in the midline the lingual tonsils and the vallecula can be imagined.[13] Just below the hyoid bone the vallecula is seen and when the probe is angled caudally the pre- and paraglottic spaces and the infrahyoid part of epiglottis is seen.[13]

The oro-pharynx
Imaging of a part of the lateral border of the mid-oropharynx can be obtained by placing the transducer vertically with its upper edge approximately 1 cm below the external auditory canal[9] and the lateral pharyngeal border and the thickness of the
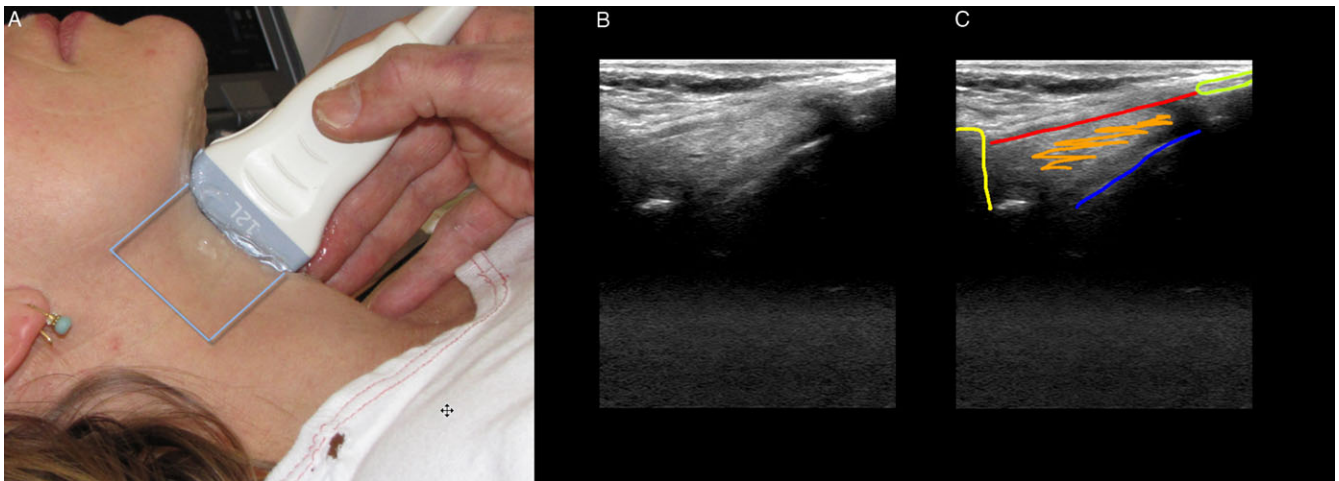
Fig. 5. Midline sagittal scan from the hyoid bone to the proximal part of the thyroid cartilage. (A) The light blue outline shows the area covered by the scanning. (B) The scanning image. (C) The shadow from the hyoid bone (yellow). The thyro-hyoid membrane (red). Posterior surface of part of epiglottis (blue). Pre-epiglottic fat (brown). Thyroid cartilage (green).

lateral parapharyngeal wall can be determined.[14] The parapharyngeal space can also be visualized via the mouth by placing the probe directly over the mucosal lining of the lateral pharyngeal wall, but this approach is difficult for the patient to tolerate.[15]

The hypo-pharynx

When performing sonography through the thyrohyoid membrane, cricothyroid space, cricothyroid membrane, thyroidal cartilage lamina, and along the posterior edge of the thyroid lamina, it is possible to locate and classify hypophryngeal tumors with a success rate as high as with computed tomography (CT) scanning.[16]

Hyoid bone

The hyoid bone is calcified early in life, and its bony shadow is an important landmark that separates the upper airway into two scanning areas: the suprahyoid and infrahyoid regions. The hyoid bone is visible on the transverse view as a superficial hyperechoic inverted U-shaped linear structure with posterior acoustic shadowing. On the sagittal and parasagittal views, the hyoid bone is visible in cross-section (Fig. 4) as a narrow hyperechoic curved structure that cast an acoustic shadow.[3]

Larynx

Because of the superficial location of the larynx, US offers images of higher resolution then CT or magnetic resonance imaging (MRI) when examined with a linear high-frequency transducer.[13] The parts of the laryngeal skeleton have different sonographic characteristics. The thyroid and the cricoid cartilages show variable but progressive calcification through life whereas the epiglottis stays hypoechoic.[17] The true vocal cords overlie muscle that is hypoechoic whereas the false cords contain echoic fat.[17] The thyrohyoid membrane runs between the caudal border of the hyoid bone and the cephalad border of the thyroid cartilage and provides a sonographic window through which the epiglottis could be visualized in all subjects with the linear transducer oriented in the transverse plane (with varying degrees of cephalad or caudad angulation).[3] The midline sagittal scan through the upper larynx from the hyoid bone cranially to the thyroid cartilage distally (Fig. 5) reveals the thyrohyoid ligament, the pre-epiglottic space containing echogenic fat[18] and posterior to this, a white line representing the laryngeal surface of the epiglottis may be seen. On parasagittal view, the epiglottis appears as a hypoechoic structure with a curvilinear shape and on transverse view it is shaped as an inverted "C". It is related anteriorly by the hyperechoic triangular pre-epiglottic space and lined posteriorly by a hyperechoic air/mucosa interface.[19] The transverse midline scan cranially to the thyroid cartilage depicted epiglottis in all subjects and revealed an average epiglottis thickness of 2.39 mm.[17] In the cricothyroid region, the probe can be angled cranially to assess the vocal cords and the arythenoid cartilages and thereafter be moved distally to access the cricoid cartilages and the subglottis.[13] When scanning transversely in the paramedian position, the following structures can be visualized starting cra-
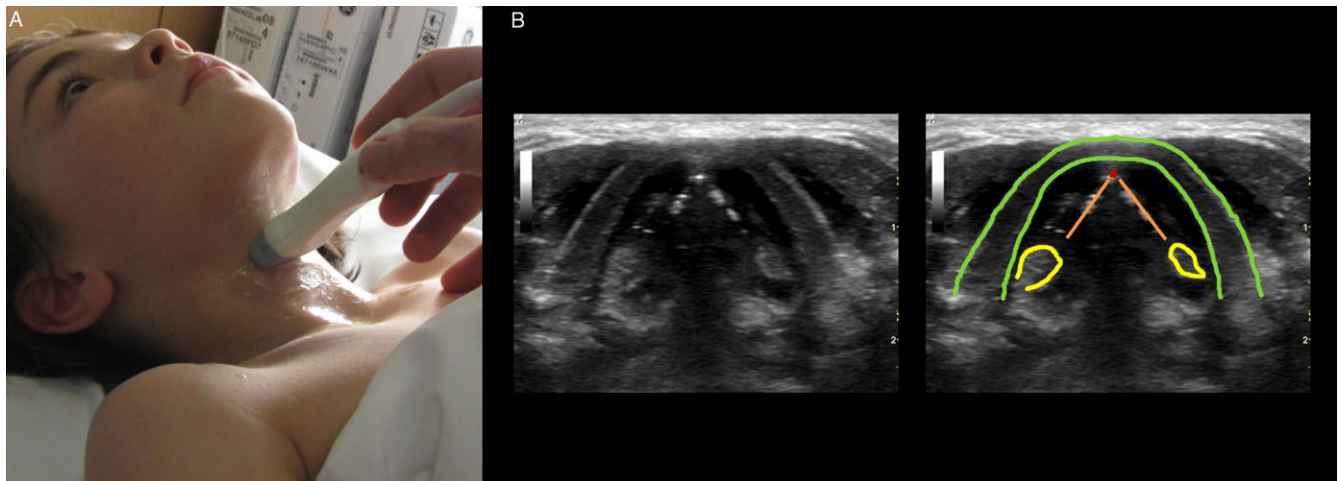
Fig. 6. (A) Transverse midline scan over the thyroid cartilage (in an 8-year-old boy). (B) Thyroid cartilage (green). Free edge of vocal cords (orange). Anterior commisure (red). Arythenoid cartilages (yellow).

nially and moving distally: faucial tonsils, lateral tongue base, lateral vallecula, strap muscles, laminae of the thyroid cartilage, the lateral cricoids cartilage and posteriorly the piriform sinuses and the cervical esophagus.[13] The laryngeal cartilage is uncalcified in the child but calcification starts in some individuals before the age of twenty and it increases with age. In subjects with un-calcified cartilage the thyroid cartilage is visible on sagittal and parasagittal views as a linear hypoechoic structure. On the transverse view, it has an inverted V shape (Fig. 6), within which the true and false vocal cords are visible.[3] At the age of 60, all individuals show sign of partial calcification and at this age approximately 40% of the cartilage at the level of the vocal cords is calcified and the calcification is seen as a strong echo with posterior acoustic shadowing.[20] Often, the anatomical structures can be visualized despite the calcifications by angling the transducer.[20] In a population who were examined because of suspicion of laryngeal pathology, a sufficient depiction of the false cords was obtained in 60% of cases, of the vocal cords in 75%, of the anterior commisure in 64%, and of the arythenoid region in 71%; however, in 16% of the cases, no endolaryngeal structures could be depicted.[20]

The vocal cords
In individuals with noncalcified thyroid cartilages, the false and the true vocal cords can be visualized through the thyroid cartilage.[18] In individuals with calcified thyroid cartilages, the vocal cords and the arythenoid cartilages can still be seen by combining the scanning from just cranially to the superior

thyroid notch angled caudally and a scanning from the cricothyroid membrane in the midline and on each side with the transducer angled 30 degrees cranially.[13] In a study group of 24 volunteers with a mean age of 30 years, the thyroid cartilage provided the best window for imaging the vocal cords. In all participants it was possible to visualize and distinguish the true and false vocal cords by moving the transducer in a cephalocaudad direction over the thyroid cartilage.[3] The true vocal cords appear as two triangular hypoechoic structures (the vocalis muscles), outlined medially by the hyperechoic vocal ligaments (Fig. 6) and are observed to oscillate and move toward the midline during phonation.[3] In a study on 229 participants with ages ranging from 2 months to 81 years the true and false cords were visible in all female participants. In males, the visibility was 100% below the age of 18 and gradually decreased to < 40% of males aged 60 or more.[21] The false vocal cords lay parallel and cephalad to the true cords, are more hyperechoic in appearance and remain relatively immobile during phonation.

Cricothyroid membrane and cricoid cartilage
The cricothyroid membrane runs between the caudal border of the thyroid cartilage and the cephalad border of the cricoid cartilage. It is clearly seen on sagittal (Fig. 7) and parasagittal views as a hyperechoic band linking the hypoechoic thyroid and cricoid cartilages.[3] The cricoid cartilage has a round hypoechoic appearance on the parasagittal view and an arch-like appearance on the transverse view.
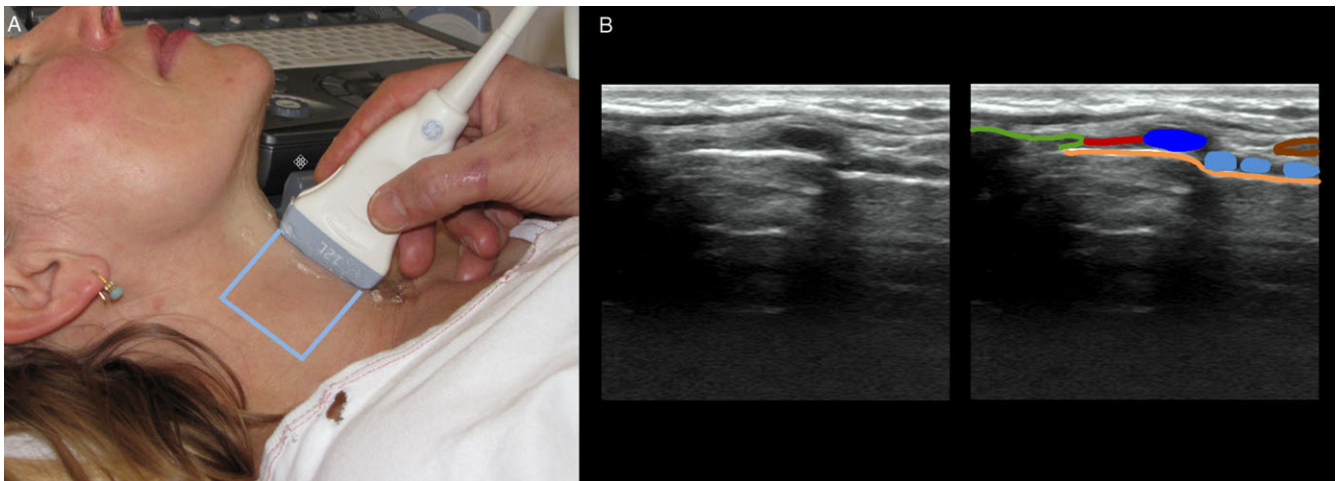
Fig. 7. (A) The linear high frequency transducer placed in the midsagittal plane, the scanning area is marked with light blue. (B) The thyroid cartilage (green). The cricoid cartilage (dark blue). Tracheal rings (light blue). The cricothyroid membrane (red). The tissue/air border (orange). The isthmus of the thyroid gland (brown). Below the orange line only artifacts are seen.

Fig. 8. Trachea and esophagus. 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). Esophagus (purple). Carotid artery (red).

Trachea

The localization of the trachea in the midline of the neck makes it serve as a useful reference point for transverse ultrasound imaging.[15] The cricoid cartilage marks the superior limit of the trachea and it is thicker then the tracheal rings below[15] and it is seen as a hypoechoic rounded structure that serves a reference point while performing the sagittal midline scan (Fig. 7). Often, the first six tracheal rings can be imagined when the neck is in mild extension.[15] The trachea is covered by skin, subcutaneous fat, the strab muscles and, at the level of the second or third tracheal ring, by the isthmus of the thyroid gland (Fig. 7). The strab muscles appear hypoechoic, and

are encased by thin hyperechoic lines from the cervical fascia.[15] A high-riding annominate artery may be identified above the sternal notch as a transverse anechoic structure crossing the trachea.[15] The tracheal rings are hypoechoic and they resemble a "string of beads" in the parasagittal and sagittal plane (Fig. 7). In the transverse view they resemble an inverted U highlighted by a hyperechoic air-mucosa interface (Fig. 8) and reverberation artifact posteriorly.[3]

Esophagus

The cervical esophagus is most often visible posterolateral to the trachea on the left side at the level of
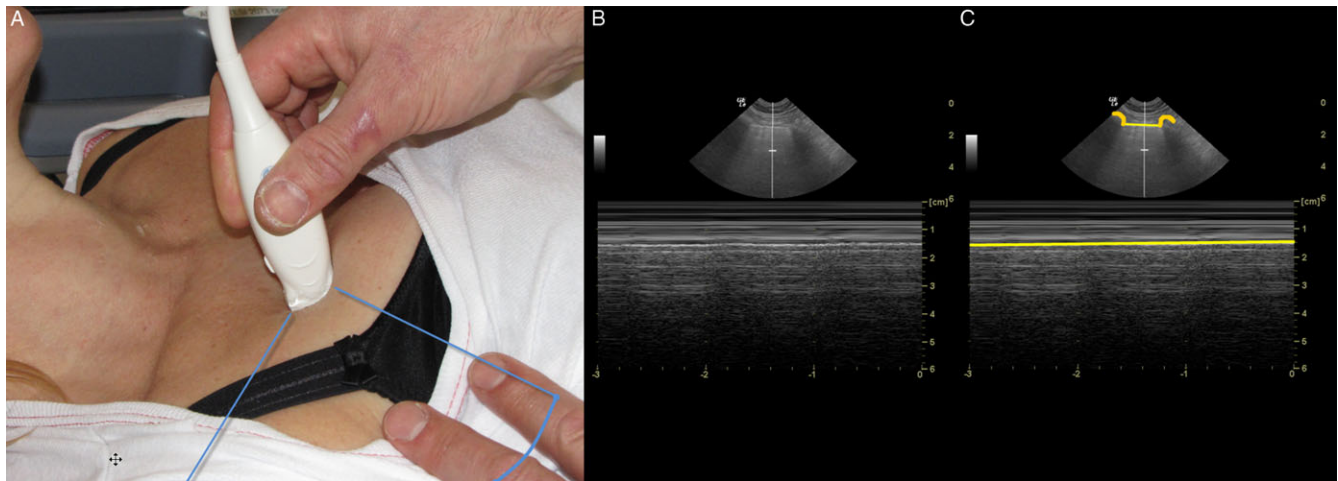
Fig. 9. Lung sliding. (A) A micro-convex probe is placed over an inter-space between two ribs during normal ventilation. The light blue line indicates the scanning area. (B) The scanning image, upper: B-mode scan, lover: M-mode. (C) The pleural line (yellow line). The ribs (orange). Note that the outline of the ribs and the pleural line forms the image of a flying bat = the "bat sign". In the M-mode image it is easy to distinguish the nonmoving tissue above the pleural line from the artifact created from the respiratory movement of the visceral pleura relative to the parietal pleura. This is called the "sea shore sign" or the "sandy beach sign", because the nonmoving part resembles waves and the artifact pattern below resembles a sandy beach.

the suprasternal notch (Fig. 8). The concentric layers of esophagus results in a very characteristic "bulls eye" appearance on the US.[15] The esophagus can be seen compress and expand with swallowing and this can be used for accurate identification.[15] A modified patient position for examining the esophagus is to slightly flex the neck with a pillow under the head and with the head turned 45 degrees to the opposite side while scanning the neck on either side,[22] this technique makes esophagus visible also on the right side in 98% of cases.

Lower trachea and bronchi
Transesophageal US displays a part of the lower trachea. When a saline-filled balloon is introduced in the trachea during cardiopulmonary bypass, it is possible to perform US through the trachea thus displaying the proximal aortic arch and the annominate artery.[23] The bronchial wall and its layers can be visualized from within the airway by passing a flexible ultrasound probe through the working channel of a flexible bronchoscope. This technique, endobronchial ultrasound, allows a reliable differentiation between airway infiltration and compression by tumor.[24]

Peripheral lung and pleura
The ribs are identifiable by their acoustic shadow, and between two ribs a hyperechoic line is visible. This line represents the interface between the soft tissue of the chest wall and air, and is called the pleural line (Fig. 9). In the spontaneously breathing or ventilated subject one can identify a kind of to-and-fro movement synchronous with ventilation, this is called "pleural sliding" or "lung sliding".[25] The movement is striking because the surrounding tissue is motionless.[26] Lung sliding is best seen dynamically, real time, or on video.* The investigation should always start by placing the probe perpendicular to the ribs and so that two rib shadows are identified. The succession of the upper rib, pleural line, and lower rib outlines a characteristic pattern (Fig. 9), the "bat sign",[27] and must be recognized to correctly identify the pleural line and avoiding interpretation errors because of a parietal emphysema.[27] Lung ultrasound examination should therefore be considered not feasible when the bat sign is not identified.[27] Lung sliding can be objectified using the time-motion mode, which highlights a clear distinction between a wave-like pattern located above the pleural line and a sand-like pattern below (Fig. 9), called the "seashore sign".[27] In breath-holding or apnea, no lung sliding, but a "lung pulse", small movements synchronous with the heartbeat, is seen instead (Fig. 10). The lung pulse can be explained as the vibrations of the heart transmitted through a motionless lung. The lung pulse can also be demonstrated in the time-motion-

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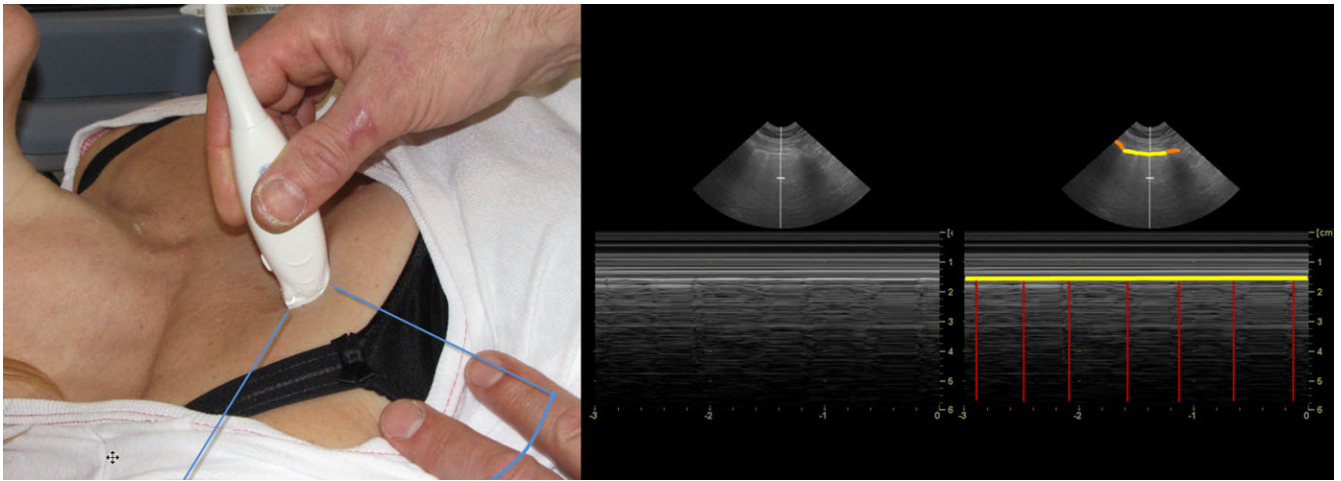*http://www.airwaymanagement.dk. Accessed April 2011.

Fig. 10. Lung pulse. In this nonventilated lung, the only movement of the pleura is created by the heartbeat that creates a subtle movement of the lungs and the pleura. This movement is visualized in the M-mode image synchronous with the heart beat, the "lung pulse". The pleural line (yellow). The superficial outline of the ribs (orange). The red lines indicate the "lung pulse".

"M"-mode. There is a strong echo from the pleural line and dominant reverberation artifacts of varying strength seen as lines parallel with the pleural line and spaced with the same distance as the distance from the skin surface to the pleural line, they are called "A lines" and are seen in both the normal and the pathological lung.[27] The "B line" is an artifact with seven features: a hydroaeric comet-tail artifact; arising from the pleural line; hyperechoic; well defined; spreading up indefinitely (spreads to the edge of the screen without fading (i.e., up to 17 cm with a probe reaching 17 cm;[27] erasing A lines; and moving with lung sliding when lung sliding is present.[28] Sparse B lines occur in normal lungs but three or more indicates pathology, for example interstitial syndrome.[28] B lines are also called "ring-down" artifacts.[29]

The diaphragm

The diaphragm and its motion can be imaged by placing a convex transducer in the subxiphoid window[30] at the mid-upper abdominal, just beneath the xiphoid process and the lower margin of liver. The transducer is tilted 45 degrees cephalically and bilateral diaphragm motion is noticed.[30] The bilateral diaphragm will move toward the abdomen when the lungs are ventilated and toward the chest during the relaxation phase. The liver and spleen movements represent the whole movement of the right and left diaphragm during respiration, and can be visualized by placing the probe in the longitudinal plane along the right anterior axillary line and along the left posterior axillary line, respectively. The movement of the most caudal margin of the liver and spleen with respiration is measured.[31]

Clinical applications

Prediction of difficult laryngoscopy in surgical patients

Intraoral sublingual US is a promising approach to examining the airway and possibly establish predictors of difficult airway management.[7] The interpretation of the sublingual US approach was later reevaluated and it remains to be determined whether this approach is useful in predicting airway difficulties.[8] In 50 morbidly obese patients, the distance from the skin to the anterior aspect of the trachea measured at the levels of the vocal cords and at the level of the suprasternal notch was significantly greater in those patients in whom laryngoscopy was difficult, even after optimization of laryngoscopy by laryngeal manipulation;[32] however, these findings could not be reproduced when the endpoint was laryngoscopy grade without the use of laryngeal manipulation for optimization of the laryngoscopic view.[33]

Evaluation of pathology that may influence the choice of airway management technique

Subglottic hemangiomas, laryngeal stenosis[34] and laryngeal cysts[13] and respiratory papillomatosis[35] (Fig. 11) can be visualized with US. A pharyngeal pouch (Zenker's diverticulum) representing a source of regurgitation and aspiration, is seen on a transverse linear high-frequency scan of the neck
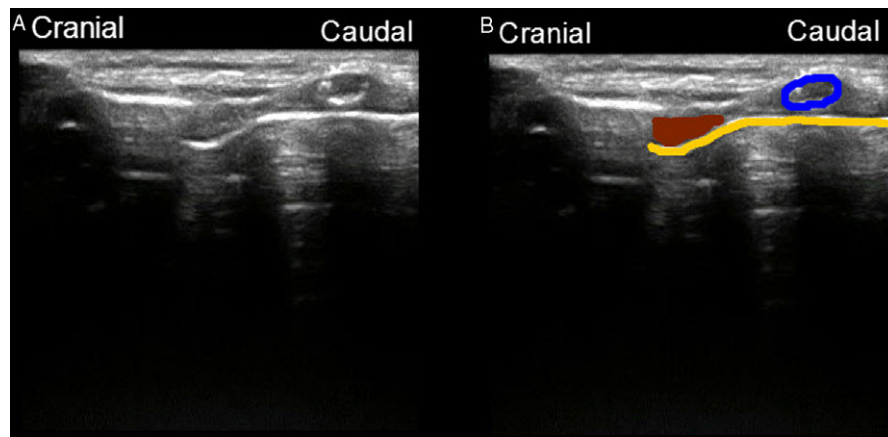
Fig. 11. Papilloma. Sagittal midline scan of the anterior neck in patient with a papilloma on the anterior tracheal wall immediately caudal to the anterior commisure. (A) The scanning image. (B) The scanning image with markings. The tissue/air border (yellow). The cricoid cartilage (blue) and the papilloma (brown).

and is located at the posterolateral aspect of the left thyroid lobe.[36] Malignancies and their relationship with the airway can be seen and quantified.

Fetal airway abnormalities such as extrinsic obstruction caused by adjacent tumors such as lymphatic malformation or cervical teratoma[37] can be visualized by prenatal US.

Diagnosing obstructive sleep apnea
The width of the tongue base measured ultrasonographically correlates with the severity of sleep-related breathing disorders, including the patients" sensation of choking during the night[10] and the thickness of the lateral pharyngeal wall as measured with US is significantly higher in patients with obstructive sleep apnea then in patients without.[14]

Evaluating prandial status
Both experimental and clinical data suggest that US can detect, and to some extend quantify, gastric content. In subjects who were randomized to either a fasting or nonfasting group and had their stomach examined with US it was found that the technique was specific in identifying a full stomach but only moderately reliable in identifying an empty stomach.[38] In another study on healthy volunteers, the cross-sectional area of the gastric antrum correlated with ingested volumes of fluid up to 300 ml, especially when the subjects were placed in the right lateral decubitus position.[39] In patients, transabdominal US can visualize gastric outlet obstruction.[40] In ICU patients, a mid-torso left mid-axillary longitudinal scanning with identification of the spleen and left hemidiaphragm and angling of the transducer anteriorly to achieve multiple tomographic planes of the left upper quadrant supplemented with sagittal-plane scanning allowed useful

identification and quantification of stomach fluid in patients immediately before urgent endotracheal intubation.[41]

Prediction of the appropriate diameter of endotracheal–, endobronchial–, or tracheostomy tube
In children[42] and young adults, US is a reliable tool for measuring the diameter of the subglottic upper airway[43] and it correlates well with MRI, which is the gold standard.

The diameter of the left mainstem bronchus, and thus the proper size of a left-sided double lumen tube, can be estimated with US. Ultrasound measurements of the outer diameter of the trachea were performed just above the sternoclavicular joint in the transverse section immediately before anesthesia. The ratio between the diameter of the trachea and of the left main-stem bronchus was obtained by examining the CT images of a series of patients. The ratio between left main-stem bronchus diameter on CT imaging and outer tracheal diameter measured with US is 0.68. The results are comparable with the results obtained using chest radiograph as a guide for selecting left double lumen tube size.[44,45] In children with tracheostomy ultrasonographic measurement of the tracheal width and of the distance from the skin to the trachea can be used to predict the size and shape of a potential replacement tracheostomy tube[46] and adequate images can be obtained by placing the ultrasound probe just superior to the tracheostoma.

Localization of the trachea
Obesity, short thick neck, neck masses, previous surgery, and/or radiotherapy to the neck, as well as thoracic pathology resulting in tracheal deviation
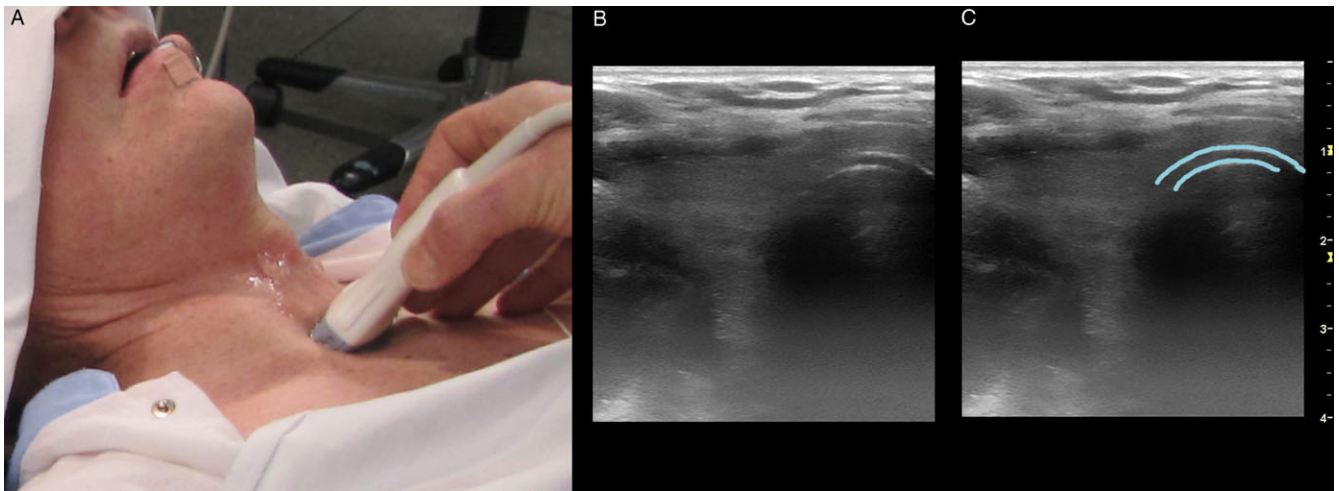
Fig. 12. Tracheal deviation. Patient with lateral deviation of the middle part of trachea. (A) The transducer is placed transversely in the midline over the suprasternal notch. (B) The scanning image. (C) The cartilage of the tracheal ring (light blue) is deviated to the patient's left side.

can make accurate localization of the trachea challenging and cumbersome. Even the addition of chest X-ray and techniques of needle aspiration to locate the trachea may be futile.[47] This situation is even more challenging in emergency cases and in cases where awake tracheostomy is chosen because of a predicted difficult mask-ventilation[47] or difficult tracheal intubation. Under such circumstances preoperative US for localization of the trachea (Fig. 12) is very useful.

Localization of the cricothyroid membrane

The cricothyroid membrane plays a crucial role in airway management but it is only correctly identified by anesthetists in 30% of cases when identification is based on surface landmarks and palpation alone.[48] US allows reliable[48] and rapid[49] identification of the cricothyroid membrane. US is a useful technique to identify the trachea prior to both elective *trans*-tracheal cannulation and emergency cricothyrotomy as demonstrated by a case concerning an obese patients with Ludwig's angina in whom it was not possible to identify the trachea by palpation, a portable ultrasound machine was used to locate it 2 cm lateral to the midline.[50] In this way, the localization of the trachea allows the clinician to approach the difficult airway either by placing a *trans*-tracheal catheter or performing a tracheostomy prior to anesthesia or to perform an awake intubation but with the added safety of having localized the cricothyroid membrane in advance in case that the awake intubation should fail and an emergency *trans*-

cricoid access should become necessary. One method for localizing the cricothyroid membrane was described as follows: A transverse, midline scan is performed from the clavicles to the mandible with a 10-MHz linear array probe and the cricothyroid membrane is identified by its characteristic echogenic artifact, the crycothyroid muscles lateral to it, and the thyroid cartilage cephalad. In a study on 50 emergency department patients the cranio-caudal level of the cricothyroid membrane was located by a longitudinal sagittal midline scan followed by sliding the probe bilaterally to localize the lateral borders of the cricothyroid membrane. The mean time to visualization of the cricothyroid membrane was 24.3 s.[49]

A simple and systematic approach to localizing the cricothyroid membrane is shown in Fig. 13.

Airway-related nerve blocks

US has casuistically been used to identify and block the superior laryngeal nerve as part of the preparation for awake fiber-optic intubation.[51] The greater horn of the hyoid bone and the superior laryngeal artery were identified and the local analgesic was injected in between. In 100 ultrasound examinations for the superior laryngeal nerve space (the space delimited by the hyoid bone, the thyroid cartilage, the pre-epiglottic space and the thyrohyoid muscle, and the membrane between the hyoid bone and the thyroid cartilage) all components of the space was seen in 81% of cases whereas there was a suboptimal, but still useful, depiction of the space in the
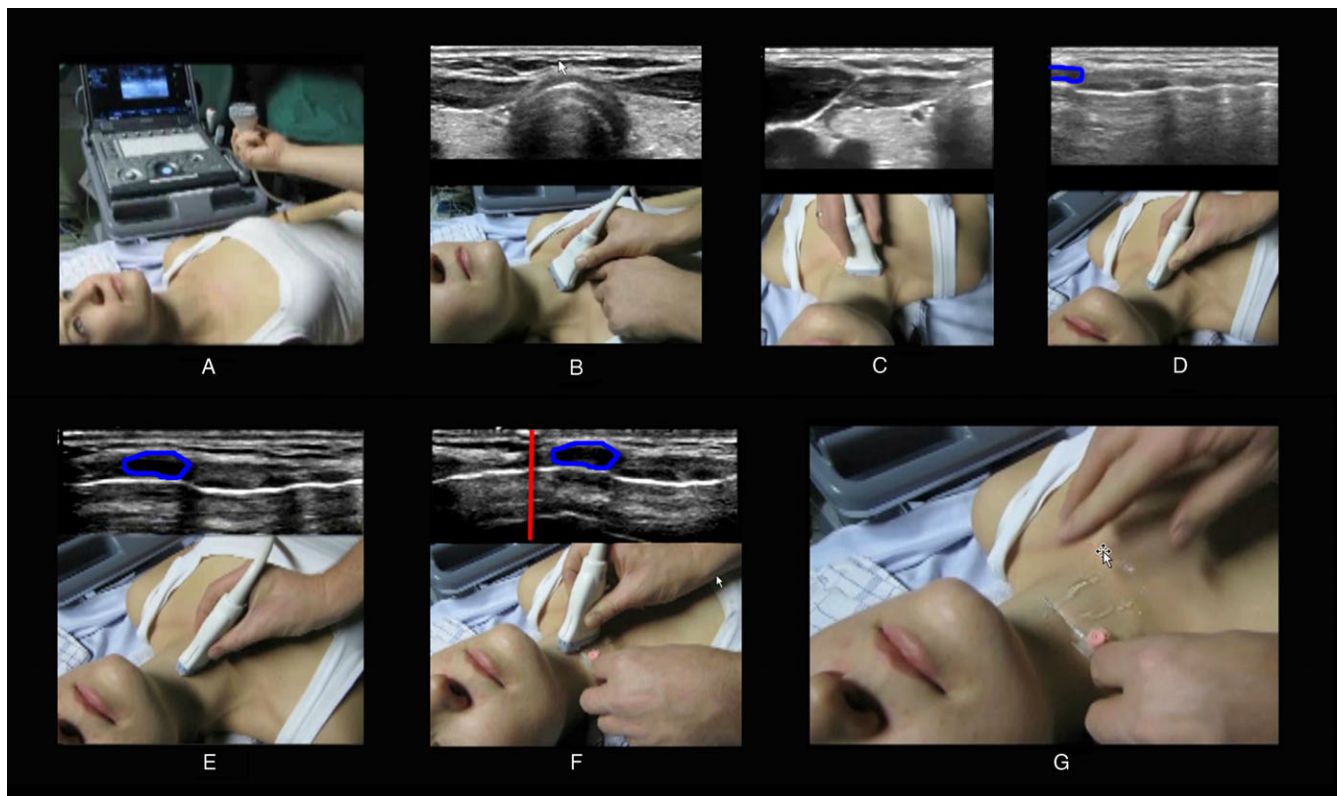
Fig. 13. Localization of the cricothyroid membrane. (A) The patient is lying supine and operator stands on the patient's right side facing the patient. (B) The linear high-frequency transducer is placed transversely over the neck just above the suprasternal notch and the trachea is seen in the midline. (C) The transducer is moved to the patient's right side so that the right border of the transducer is superficial to the midline of the trachea. (D) The right end of the transducer is kept in the midline of the trachea while the left end of the transducer is rotated into the sagittal plane resulting in a longitudinal scan of the midline of the trachea, the caudal part of the cricoid cartilage is seen (blue). (E) The transducer is moved cranially and the cricoid cartilage (blue) is seen as a slightly elongated structure that is significantly larger and more anteriorly than the tracheal rings. (F) A needle is moved under the transducer from the cranial end, used only as a marker. The shadow (red line) is just cranially to the cranial border of the cricoid cartilage (blue). (G) The transducer is moved and the needle indicates the distal part of the cricothyroid membrane.

remaining 19% of cases. The superior laryngeal nerve itself was not seen.‡

Confirmation of endotracheal tube placement
The confirmation of whether the tube enters the trachea or the esophagus can be made either directly, real time by scanning the anterior neck during the intubation, indirectly by looking for ventilation at the pleural or the diaphragmatic level, or by combining these techniques. The direct confirmation has the advantage that an accidental esophageal intubation is recognized immediately, before ventilation is initiated and thus before air is

forced into the stomach resulting in an increased risk of emesis and aspiration. Confirmation at the pleural level has the advantage of, at least to some extent, distinguishing between tracheal and endo-bronchial intubation. Both the direct and the indirect confirmation have the advantage over cap-nography that it can be applied in the very low-cardiac output situation. US has the advantage over auscultation that it can be performed in noisy envi-ronments, such as in helicopters. In a cadaver model where a 7.5 MHz curved probe was placed longitudinally over the cricothyroid membrane, it was possible for residents given only 5 min of train-ing in the technique to correctly identify esopha-geal intubation (97% sensitivity) when this was performed *during* the intubation, dynamically. When the examination was performed *after* the intubation, the sensitivity was very poor.[52]

‡Abstract presented at the ASA congress October 2011 in San Diego: http://www.asaabstracts.com/strands/asaabstracts/ abstract.htm;jsessionid=C986F78824818B55DDE240C3C3B533 FD?year=2010&index=17&absnum=2049. Accessed April 2011.

In 40 elective patients, a 3–5 MHz curved transducer placed at the level of the cricothyroid membrane and held at a 45-degree angle facing cranially allowed detection of all five accidental esophageal intubations. Tracheal passage of the tube was seen as a brief flutter deep to the thyroid cartilage whereas esophageal intubation created a clearly visible bright (hyperechoic) curved line with a distal dark area (shadowing) appearing on one side of, and deep to, the trachea.[53]

It was possible to detect both tracheal and esophageal intubation in all 33 patients with normal airways who were intubated electively in both trachea and esophagus in random order, and in 150 patients intubated either in the trachea or in the esophagus,[54] and who had a linear probe placed transversely on the anterior neck just superior to the suprasternal notch. It was concluded that: Skilled ultrasonographers in a controlled operating room setting can consistently detect passage of a tracheal tube into either the trachea or esophagus in normal airways.[55] In children, direct confirmation of tracheal tube placement by scanning via the cricothyroid membrane required multiple views, the ultrasonographic examination was apparently performed after the intubation making the comparison with other studies difficult[56] and the feasibility of that approach has been challenged.[57]

Indirect confirmation of tube placement in 15 patients was performed by using a portable handheld ultrasound machine and routinely scanning in the third and fourth intercostals space on both sides during the phases of pre-oxygenation, apnea, bag-mask ventilation, during intubation, and during positive pressure ventilation after the intubation. Tube placement was determined in all cases.[58] The color power Doppler function was used as a supplement to observing lung sliding to detect that a lung was ventilated.[58] The distinction between tracheal and endobronchial intubation can be made by scanning the lung bilaterally. If the there is pleural sliding on one side and lung pulse on the other, it indicates that the tip of the tube is in the main stem bronchus on the side where lung sliding is observed. The tube is withdrawn until lung sliding is observed bilaterally indicating that the tip of the tube is again placed in the trachea.[59] Indirect confirmation of intubation by detection of a "sliding lung" was studied in fresh cadavers where the tip of the tube was placed either in esophagus, trachea, or right main-stem bronchus. A high sensitivity (95–100%) was found for detection of esophageal vs. airway (trachea or right men stem bronchus) intubation.

The sensitivity for distinguishing a right main stem bronchus intubation from tracheal intubation was lover (69–78%). This likely resulted from transmitted movement of the left lung from expansion of the right lung.[60] Indirect confirmation of intubation by depicting the movement of the diaphragm bilaterally has been shown to be useful for distinction between esophageal and tracheal intubation in a pediatric population.[30] When the technique is used to distinguish between main stem bronchus vs. tracheal intubation, diaphragmatic ultrasound was not equivalent to chest radiography for endotracheal tube placement within the airway.[61] The *combination* of the direct transverse scan on the neck at the level of the cricothyroid membrane and lung ultrasound detecting lung sliding in 30 emergency department patients who needed tracheal intubation correctly detected the three cases of esophageal intubation even in the presence of four cases of pneumohemothorax.[62] The combination of the direct transverse scan on the neck at the level of the thyroid lobes combined with lung ultrasound has casuistically demonstrated its value by being able to detect esophageal intubation in a patient in whom laryngoscopy was difficult in the clinical emergency setting.[63] Filling the cuff with fluid helps in seeing the cuff position.[64] Using a metal stylet does not augment visualization of the endotracheal tube.[65] In children, when placing the transducer at the level of the glottis, the vocal cords were always visible and the passing of the tracheal tube was visible in all children and characterized by the widening of the vocal cords.[66] US is also useful in confirming the correct position of a double-lumen tube.[44,67]

Authors recommendations
Perform a transverse scan over the trachea just above the sterna notch. Note the location and appearance of the esophagus. Let the intubation be performed. If the tube is seen passing in the esophagus, remove it without starting to ventilate the patient and make another intubation attempt, possibly using another technique. If the tube is not seen, or if it is seen in the trachea, have the patient ventilated via the tube. Move the transducer to the mid axillary lines, and look for lung sliding bilaterally. If there is bilateral lung sliding it is a confirmation that the tube is in the airway, but a main stem bronchus intubation cannot be ruled out. If there is one-sided lung sliding and lung pulse on the other side, then a main-stem intubation is likely, and the tube can be removed gradually until bilateral sliding is present. If there is no lung sliding on either side, but lung
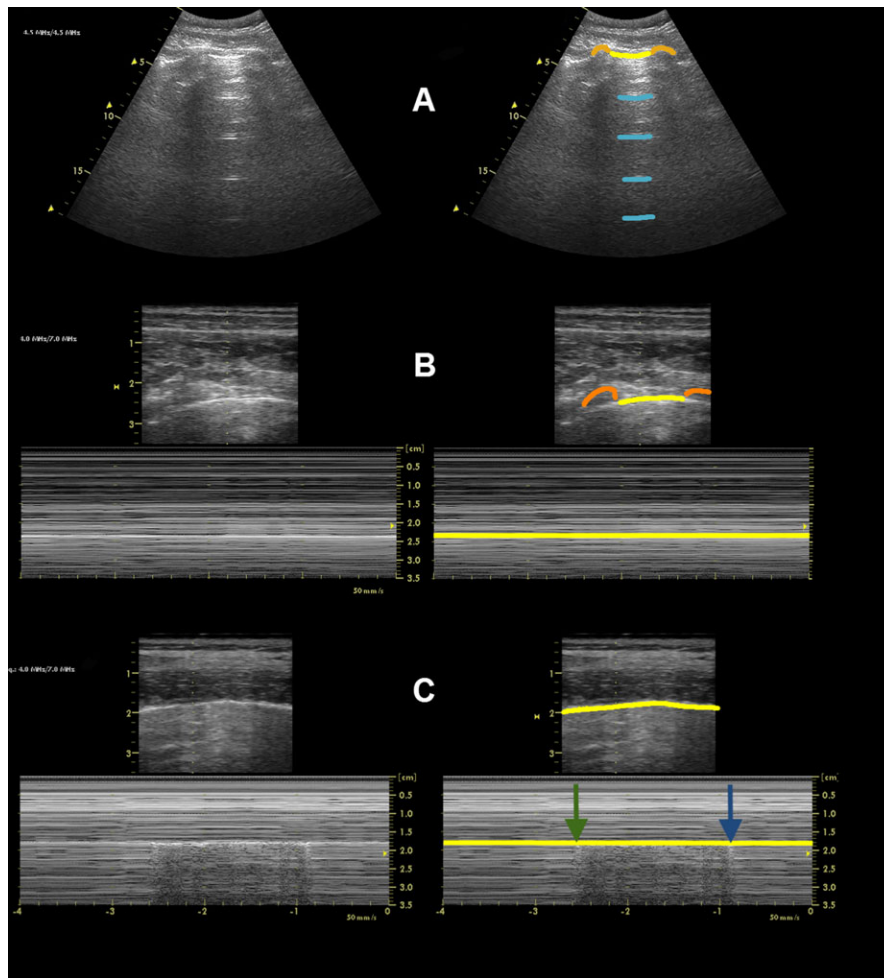
Fig. 14. Pneumothorax. (A) Scanning image obtained with a convex transducer in a rib interspace. The pleural line (yellow) represents the surface of the parietal pleura. The ribs (orange) create underlying shadows. The "A lines" (light blue) are reverberation artifacts from the pleural line, they are dispersed with the same distance between the A lines as between the skin surface and the pleural line. (B) Everything profound to the pleural line is artifact. There is absence of pleural sliding and absence of lung pulse. The M-mode image consists of only parallel lines, called the "stratosphere sign". (C) The green arrow represents the "lung point", the moment where the visceral pleura just comes in contact with the parietal pleura right at the location of the transducer. In the time interval from the green to the blue arrow the two pleural layers are in contact with each other and form the "lung sliding" pattern. After the time represented by the blue arrow, the two pleural layers are no longer in contact and the "stratosphere sign" is seen. The lung point can be difficult to see on the static B-mode image whereas it is easy to recognize in the dynamic, real-time, B-mode scanning. Courtesy Erik Sloth, Department of Anaesthesiology and Intensive Care Medicine, Aarhus University Hospital, Skejby, Denmark.

pulse, there is a small risk of the tube having entered the esophagus. If there is neither lung pulse nor lung sliding, then a pneumothorax should be expected.

Tracheostomy
Accurate localization of the trachea in the absence of surface landmarks can be very challenging, cumbersome, and preoperative US for localization of the trachea (Fig. 14) is very suitable for both surgical[47] and percutaneous dilatational tracheostomy. In children, preoperative US is of value in verifying the precise tracheostomy position and thereby preventing subglottic damage of the cricoid cartilage and the first tracheal ring, of hemorrhage because of abnormally placed or abnormally large blood vessels and of pnemothorx.[68]

Percutaneous dilatational tracheostomy (PDT)
US allows localization of the trachea, visualization of the anterior tracheal wall and pre-tracheal tissue including blood vessels,[69] and selection of the optimal intercartilaginous space for placement of the tracheostomy tube.[70] The distance from the skin surface to the tracheal lumen can be measured in order to predetermine the length of the puncture cannula that is needed to reach the tracheal lumen without perforating the posterior wall.[71] The distance can also be used to determine the optimal length of the tracheostomy cannula.[72] The ultrasound-guided PDT has been applied in a case where bronchoscope-guided technique was abandoned.[71] Cases of fatal bleeding following PDT revealed that the tracheostomy level on autopsy turned out to be much more caudal then intended, and that the innominate vein and the arch of the aorta had been eroded. It is likely that the addition of an ultrasonographic examination to determine the level for the PDT and to avoid blood vessels can diminish this risk.[73] US guided PDT results in a significant lower rate of cranial misplacement of the tracheostomy tube than "blind" placement.[70]

Bronchoscope-guided PDT often results in considerable hypercapnia whereas ultrasound Doppler-guided PDT does not.[74]

In a prospective series of 72 PDTs, the combination of US and bronchoscopy was applied. Before the procedures all subjects had their pretracheal space examined with US, which led to a change in the planned puncture site in 24% of cases and to change of the procedure to a surgical tracheostomy in one case where the ultrasound examination revealed a goiter with extensive subcutaneous vessels.[75] A different approach, namely trying to follow the needle during its course through the tissue overlying the trachea was tried. A small curved transducer was used in the transverse plane to localize the tracheal midline and then turned to the longitudinal plane to allow needle puncture in the inline plane, in order to follow the needle's course from the skin surface to the trachea. After guide-wire insertion at CT-scan was performed that showed that although all punctures successfully entered the trachea in first (89%) or second (11%) attempt, the guide-wire was placed laterally to the ideal midline position in five of nine cadavers.[76] Another approach using real-time ultrasonic guidance with visualization of the needle path with a linear high-frequency transducer placed transversely over the trachea was more successful and resulted in visualization of the needle path and satisfactory guide-wire placement in all of 13 patients.[77]

Confirmation of gastric tube placement

Abdominal US performed in the ICU had a 97% sensitivity for detecting correct gastric placement of a weighted-tip nasogastric tube and radiography correctly identified all catheters, but the radiographic confirmation lasted on average 180 min (113–240) (median and range) in contrast to the sonographic examinations that lasted 24 min (11–53). The authors conclude that bedside sonography performed by nonradiologists is a sensitive method for confirming the position of weighted-tip nasogastric feeding tubes and is easily taught to ICU physicians and that conventional radiography could be reserved for cases in which sonography is inconclusive.[78]

A Sengstaken–Blakemore tube can be applied for severe esophageal variceal bleeding but there are considerable complications, including deaths, from esophageal rupture after inadvertent inflation of the gastric balloon in the esophagus.[79] US of the stomach can aid in the rapid confirmation of correct placement. If the Sengstaken tube is not directly visible, inflation of 50 ml air via the stomach (not the gastric balloon!) lumen of the tube should lead to a characteristic jet of echogenic bubbles within the stomach. The gastric balloon is slowly inflated under direct sonographic control and usually appears as a growing echogenic circle within the stomach.[79]

Diagnosis of pneumothorax

US is as effective as chest radiography in detecting or excluding pneumothorax.[29] In the intensive care setting it is even more sensitive as it is able to establish the diagnosis in the majority of patients in whom the pneumothorax is invisible on X-ray but diagnosed by CT-scan.[27] In patients with multiple injuries, US was found to be faster and had a higher sensitivity and accuracy compared with chest radiography.[80] When lung sliding or lung pulse is present on ultrasonographic examination, it tells you that at that specific point, under the transducer, the two pleural layers are in close proximity to each other, that is there is no pneumothorax right there. If there is free air, pneumothorax, in the part of the pleural cavity underlying the transducer, no lung sliding or lung pulse will be seen and A lines (Fig. 14) will be more dominant.[27] In the M-mode, you will see the "stratosphere sign": Only parallel lines through all of the depth of the image (Fig. 14). If the transducer is placed right at the border of the pneumothorax, right where the visceral pleural intermittently is in contact with the parietal pleura, you will see the lung point (Fig. 14). The lung point is seen as a sliding lung alternating with A lines synchronous with ventilation. The lung point is pathognomonic for pneumothorax. If a pneumothorax is suspected, you can systematically "map" the rib interspaces of the thoracic cavity and confirm or rule out a pneumothorax. The lung point is best seen on real-time US or on a video recording.§ The detection of lung sliding has a negative predictive value of 100%[26] meaning that when lung sliding is seen it is ruled out that there is a pneumothorax of the part of the lung beneath the ultrasound probe. For the diagnosis of occult pneumothorax, the abolition of lung sliding alone had a sensitivity of 100% and a specificity of 78%. Absent lung sliding plus the A line sign had a sensitivity of 95% and a specificity of 94%. The lung point had a sensitivity of 79% and a specificity of 100%.[27] A systematic approach is recommended when examining the supine patient. The anterior chest wall can be divided in quadrants and

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§http://www.airwaymangement.dk. Accessed April 2011.

the probe is first placed at the most superior aspect of the thorax with respect to gravity, in other words, the lower part of the anterior chest wall in supine patients. The probe is positioned on each of the four quadrants of the anterior area followed by the lateral chest wall between the anterior and posterior axillary lines and the rest of the accessible part of the thorax.[27]

If the suspicion of a pneumothorax arises intra-operatively, US is the fastest way to confirm or rule out a pneumothorax, especially taken into consideration that an anterior pneumothorax is often undiagnosed in the supine patient subjected to plain anterior–posterior X-ray and that the gold standard, CT, is very difficult to apply in this situation. US is an obvious first choice in diagnostics if a pneumothorax is suspected during or after central venous cannulation or nerve blockade, especially if US is already in use for the procedure itself and thus is immediately available.

Differentiation between different types of lung- and pleura-pathology

Seventy percent of the pleural surface is accessible to ultrasound examination.[29] that can detect pleural effusion and differentiate between pleural fluid and pleural thickening and is more accurate than radiographic measurement in the quantification of pleural effusion.[29] Routine use of lung US in the ICU setting can lead to a reduction of the number of chest radiographs and CT scans performed.[81]

Prediction of successful extubation

In adult ventilator-treated patients, the transducer was placed on the cricothyroid membrane with a transverse view of the larynx, and the width of the air column were significantly smaller in the group of patients who developed post-extubation stridor.[82] The number of patients in the stridor group was small, four patients, and the results need to be evaluated in larger studies. Intubated patients receiving mechanical ventilation in a medical ICU had their breathing force evaluated by US. The probe was placed along the right anterior axillary line and the left posterior axillary line for measurement of liver and spleen displacement in cranio-caudal aspects, respectively. The cutoff value of diaphragmatic displacement for predicting successful extubation was determined to be 1.1 cm. The liver and spleen displacements measured in the study is thought to reflect the "global" functions of the respiratory muscles, and this method is a good parameter of

respiratory muscle endurance and predictor of extubation succes.[31]

Special techniques and indications and future aspects

The lateral position of a laryngeal mask airway cuff can be seen if the cuff is filled with fluid but the fluid damages the cuff on subsequent autoclaving.[64] Airway obstruction because of a pre-vertebral hematoma following difficult central line insertion may be prevented by using US for this procedure.[83] The larynx can be depicted from the luminal side by filling the larynx and the trachea above the cuff of the endotracheal tube with 0.9% saline to obtain sufficient tissue connection and prevent the retention of air bubbles in the anterior commissure.[84] The technique involves a thin catheter high-frequency probe with a rotating mirror spread the ultrasound ray, producing a 360° image rectilinear to the catheter.[84,85] 3-D and pocket size US devices are likely to move the boundaries for both the quality and the availability of ultrasonographic imaging of the airway.

How to learn airway US

The following studies give an insight in what, and how little, it takes to learn basic airway US. After 8.5 h of focused training comprising a 2.5-h didactic course, which included essential views of normal and pathologic conditions and three hands-on sessions of 2 h, physicians without previous knowledge of US can competently perform basic general ultrasonic examinations.[5] The examinations were aimed at diagnosing the presence of pleural effusion, intra-abdominal effusion, acute cholecystitis, intrahepatic biliary duct dilation, obstructive uropathy, chronic renal disease, and deep venous thrombosis. For questions with a potential therapeutic impact, the physicians answered 95% of the questions correctly.[5] The sonographic experience needed to make a correct diagnosis is probably mostly task specific. In other words, the basic skill required to detect a pleural effusion may be acquired in minutes and may then improve with experience.[86] A 25-min instructional session, including both a didactic portion and hands-on practice, was given to critical care paramedics/nurses who were part of a helicopter critical care transport team. The instructional session focused solely on the detection of the presence or absence of the lung sliding including secondary ultrasonographic techniques for the

detection of the lung sliding, including power Doppler and M-mode US. The participant's performance was studied on fresh cadavers. The presence or absence of the lung sliding was correctly identified in 46 of the 48 trials, for a sensitivity and specificity of 96.9% and 93.8%. At a 9-month follow-up, the presence or absence of the lung sliding was correctly identified in all 56 trials, resulting in a sensitivity and specificity of 100%.[87] In a cadaver model where a 7.5-MHz curved probe was placed longitudinally over the cricothyroid membrane, it was possible for residents given only 5 min of training in the technique to correctly identify esophageal intubation (97% sensitivity) when this was performed dynamically, during the intubation. When the examination was performed after the intubation, the sensitivity was poor.[52]

Conclusion

US

– has many advantages for imaging the airway – it is safe, quick, repeatable, portable, widely available, and gives real-time dynamic images relevant for several aspects of management of the airway.

– must be used *dynamically* for maximum benefit in airway management and in direct conjunction with the airway management: Immediately before, during, and after, airway interventions.

– can be used for direct observation of whether the tube enters the trachea or the esophagus by placing the ultrasound probe transversely on the neck at the level of the suprasternal notch during intubation, thus confirming intubation *without* the need for ventilation or circulation.

– can be applied before anesthesia induction and diagnose several conditions that affect airway management, but it remains to be determined in which patients the predictive value of such an examination is high enough to recommend this as a routine approach to airway management planning.

– can identifiy the croicothyroid membrane prior to management of a difficult airway.

– can confirm ventilation by observing lung sliding bilaterally.

– should be the first diagnostic approach when a pneumothorax is suspected intraoperatively or during initial trauma evaluation.

– can improve percutaneous dilatational tracheostomy by identifying the correct tracheal-ring interspace, avoiding blood vessels, and determining the depth from the skin to the tracheal wall

Acknowledgements

References

1. Cook TM, Woodall N, Frerk C, Project obotFNA. Major complications of airway management in the UK: results of the Fourth National Audit Project of the Royal College of Anaesthetists and the Difficult Airway Society. Part 1: anaesthesia. Br J Anaesth 2011; 106: 617–31.

2. Cook TM, Woodall N, Harper J, Benger J, Project obotFNA. Major complications of airway management in the UK: results of the Fourth National Audit Project of the Royal College of Anaesthetists and the Difficult Airway Society. Part 2: intensive care and emergency departments. Br J Anaesth 2011; 106: 632–42.

3. Singh M, Chin KJ, Chan VW, Wong DT, Prasad GA, Yu E. Use of sonography for airway assessment: an observational study. J Ultrasound Med 2010; 29: 79–85.

4. Sites BD, Brull R, Chan VW, Spence BC, Gallagher J, Beach ML, Sites VR, Abbas S, Hartman GS. Artifacts and pitfall errors associated with ultrasound-guided regional anesthesia. Part II: a pictorial approach to understanding and avoidance. Reg Anesth Pain Med 2007; 32: 419–33.

5. Chalumeau-Lemoine L, Baudel JL, Das V, Arrivé L, Noblinski B, Guidet B, Offenstadt G, Maury E. Results of short-term training of naïve physicians in focused general ultrasonography in an intensive-care unit. Intensive Care Med 2009; 35: 1767–71.

6. Maniere-Ezvan A, Duval JM, Darnault P. Ultrasonic assessment of the anatomy and function of the tongue. Surg Radiol Anat 1993; 15: 55–61.

7. Tsui BC, Hui CM. Sublingual airway ultrasound imaging. Can J Anaesth 2008; 55: 790–1.

8. Tsui BC, Hui CM. Challenges in sublingual airway ultrasound interpretation. Can J Anaesth 2009; 56: 393–4.

9. Miller JJ, Sonies BC. Dynamic imaging of the tongue, larynx, and pharynx during swallowing. Orloff LA ed. San Diego: Plural Publishing, 2008.

10. Lahav Y, Rosenzweig E, Heyman Z, Doljansky J, Green A, Dagan Y. Tongue base ultrasound: a diagnostic tool for predicting obstructive sleep apnea. Ann Otol Rhinol Laryngol 2009; 118: 179–84.

11. Volk J, Kadivec M, Mušič MM, Ovsenik M. Three-dimensional ultrasound diagnostics of tongue posture in children with unilateral posterior crossbite. Am J Orthod Dentofacial Orthop 2010; 138: 608–12.

12. Ueda D, Yano K, Okuno A. Ultrasonic imaging of the tongue, mouth, and vocal cords in normal children: establishment of basic scanning positions. J Clin Ultrasound 1993; 21: 431–9.

13. Beale TJ, Rubin JS. Laryngeal ultrasonography. Orloff LA ed. San Diego: Plural Publishing, 2008.

14. Liu KH, Chu WC, To KW, Ko FW, Tong MW, Chan JW, Hui DS. Sonographic measurement of lateral parapharyngeal wall thickness in patients with obstructive sleep apnea. Sleep 2007; 30: 1503–8.

15. Gourin CG, Orloff LA. Normal head and neck ultrasound anatomy. Orloff LA, ed. San Diego: Plural Publishing, 2008.

16. Xia CX, Zhu Q, Cheng Y, Zhao HX, Jin ZZ. Sonographic assessment of hypopharyngeal carcinoma: preliminary study. J Ultrasound Med 2011; 30: 217–25.

17. Werner SL, Jones RA, Emerman CL. Sonographic assessment of the epiglottis. Acad Emerg Med 2004; 11: 1358–60.

18. Loveday E. The larynx. Ahuja A, Evans R eds. Cambridge: Cambridge University Press, 2008.
19. Prasad A, Singh M, Chan VW. Ultrasound imaging of the airway. Can J Anaesth 2009; 56: 868–9; author reply 69–70.
20. Bozzato A, Zenk J, Gottwald F, Koch M, Iro H. [Influence of thyroid cartilage ossification in laryngeal ultrasound]. Laryngorhinootologie 2007; 86: 276–81.
21. Hu Q, Zhu SY, Luo F, Gao Y, Yang XY. High-frequency sonographic measurements of true and false vocal cords. J Ultrasound Med 2010; 29: 1023–30.
22. Mateen MA, Kaffes AJ, Sriram PV, Rao GV, Reddy DN. Modified technique of high-resolution ultrasonography of the normal cervical esophagus. J Gastroenterol Hepatol 2006; 21: 1660–3.
23. Li YL, Wong DT, Wei W, Liu J. A novel acoustic window for trans-oesophageal echocardiography by using a saline-filled endotracheal balloon. Br J Anaesth 2006; 97: 624–9.
24. Herth F, Ernst A, Schulz M, Becker H. Endobronchial ultrasound reliably differentiates between airway infiltration and compression by tumor. Chest 2003; 123: 458–62.
25. Razzaq QM. Use of the "sliding lung sign" in emergency bedside ultrasound. Eur J Emerg Med 2008; 15: 238–41.
26. Lichtenstein DA, Menu Y. A bedside ultrasound sign ruling out pneumothorax in the critically ill. Lung sliding. Chest 1995; 108: 1345–8.
27. Lichtenstein DA, Mezière G, Lascols N, Biderman P, Courret JP, Gepner A, Goldstein I, Tenoudji-Cohen M. Ultrasound diagnosis of occult pneumothorax. Crit Care Med 2005; 33: 1231–8.
28. Lichtenstein DA, Mezière GA. Relevance of lung ultrasound in the diagnosis of acute respiratory failure: the BLUE protocol. Chest 2008; 134: 117–25.
29. Sartori S, Tombesi P. Emerging roles for transthoracic ultrasonography in pleuropulmonary pathology. World J Radiol 2010; 2: 83–90.
30. Hsieh KS, Lee CL, Lin CC, Huang TC, Weng KP, Lu WH. Secondary confirmation of endotracheal tube position by ultrasound image. Crit Care Med 2004; 32: S374–7.
31. Jiang JR, Tsai TH, Jerng JS, Yu CJ, Wu HD, Yang PC. Ultrasonographic evaluation of liver/spleen movements and extubation outcome. Chest 2004; 126: 179–85.
32. Ezri T, Gewürtz G, Sessler DI, Medalion B, Szmuk P, Hagberg C, Susmallian S. Prediction of difficult laryngoscopy in obese patients by ultrasound quantification of anterior neck soft tissue. Anaesthesia 2003; 58: 1111–4.
33. Komatsu R, Sengupta P, Wadhwa A, Akça O, Sessler DI, Ezri T, Lenhardt R. Ultrasound quantification of anterior soft tissue thickness fails to predict difficult laryngoscopy in obese patients. Anaesth Intensive Care 2007; 35: 32–7.
34. Garel C, Contencin P, Polonovski JM, Hassan M, Narcy P. Laryngeal ultrasonography in infants and children: a new way of investigating. Normal and pathological findings. Int J Pediatr Otorhinolaryngol 1992; 23: 107–15.
35. Bryson PC, Leight WD, Zdanski CJ, Drake AF, Rose AS. High-resolution ultrasound in the evaluation of pediatric recurrent respiratory papillomatosis. Arch Otolaryngol Head Neck Surg 2009; 135: 250–3.
36. Lixin J, Bing H, Zhigang W, Binghui Z. Sonographic diagnosis features of Zenker diverticulum. Eur J Radiol [Epub ahead of print].
37. Courtier J, Poder L, Wang ZJ, Westphalen AC, Yeh BM, Coakley FV. Fetal tracheolaryngeal airway obstruction: prenatal evaluation by sonography and MRI. Pediatr Radiol 2010; 40: 1800–5.
38. Jacoby J, Smith G, Eberhardt M, Heller M. Bedside ultrasound to determine prandial status. Am J Emerg Med 2003; 21: 216–9.
39. Perlas A, Chan VW, Lupu CM, Mitsakakis N, Hanbidge A. Ultrasound assessment of gastric content and volume. Anesthesiology 2009; 111: 82–9.
40. Shiver SA, Blaivas M. Gastric outlet obstruction secondary to linitis plastica of the stomach as shown on transabdominal sonography. J Ultrasound Med 2004; 23: 989–92.
41. Koenig SJ, Lakticova V, Mayo PH. Utility of ultrasonography for detection of gastric fluid during urgent endotracheal intubation. Intensive Care Med 2011; 37: 627–31.
42. Shibasaki M, Nakajima Y, Ishii S, Shimizu F, Shime N, Sessler DI. Prediction of pediatric endotracheal tube size by ultrasonography. Anesthesiology 2010; 113: 819–24.
43. Lakhal K, Delplace X, Cottier JP, Tranquart F, Sauvagnac X, Mercier C, Fusciardi J, Laffon M. The feasibility of ultrasound to assess subglottic diameter. Anesth Analg 2007; 104: 611–4.
44. Sustić A. Role of ultrasound in the airway management of critically ill patients. Crit Care Med 2007; 35: S173–7.
45. Sustic A, Miletic D, Protic A, Ivancic A, Cicvaric T. Can ultrasound be useful for predicting the size of a left double-lumen bronchial tube? Tracheal width as measured by ultrasonography versus computed tomography. J Clin Anesth 2008; 20: 247–52.
46. Hardee PS, Ng SY, Cashman M. Ultrasound imaging in the preoperative estimation of the size of tracheostomy tube required in specialised operations in children. Br J Oral Maxillofac Surg 2003; 41: 312–6.
47. Munir N, Hughes D, Sadera G, Sherman IW. Ultrasound-guided localisation of trachea for surgical tracheostomy. Eur Arch Otorhinolaryngol 2010; 267: 477–9.
48. Elliott DS, Baker PA, Scott MR, Birch CW, Thompson JM. Accuracy of surface landmark identification for cannula cricothyroidotomy. Anaesthesia 2010; 65: 889–94.
49. Nicholls SE, Sweeney TW, Ferre RM, Strout TD. Bedside sonography by emergency physicians for the rapid identification of landmarks relevant to cricothyrotomy. Am J Emerg Med 2008; 26: 852–6.
50. Orr JA, Stephens RS, Mitchell VM. Ultrasound-guided localisation of the trachea. Anaesthesia 2007; 62: 972–3.
51. Manikandan S, Neema PK, Rathod RC. Ultrasound-guided bilateral superior laryngeal nerve block to aid awake endotracheal intubation in a patient with cervical spine disease for emergency surgery. Anaesth Intensive Care 2010; 38: 946–8.
52. Ma G, Davis DP, Schmitt J, Vilke GM, Chan TC, Hayden SR. The sensitivity and specificity of transcricothyroid ultrasonography to confirm endotracheal tube placement in a cadaver model. J Emerg Med 2007; 32: 405–7.
53. Milling TJ, Jones M, Khan T, Tad-y D, Melniker LA, Bove J, Yarmush J, SchianodiCola J. Transtracheal 2-d ultrasound for identification of esophageal intubation. J Emerg Med 2007; 32: 409–14.
54. Muslu B, Sert H, Kaya A, Demircioglu RI, Gözdemir M, Usta B, Boynukalin KS. Use of sonography for rapid identification of esophageal and tracheal intubations in adult patients. J Ultrasound Med 2011; 30: 671–6.
55. Werner SL, Smith CE, Goldstein JR, Jones RA, Cydulka RK. Pilot study to evaluate the accuracy of ultrasonography in confirming endotracheal tube placement. Ann Emerg Med 2007; 49: 75–80.
56. Galicinao J, Bush AJ, Godambe SA. Use of bedside ultrasonography for endotracheal tube placement in pediatric patients: a feasibility study. Pediatrics 2007; 120: 1297–303.
57. Sundaram V, Kumar A, Kumar P. Bedside ultrasonography and endotracheal tube placement: a long way to go. Pediatrics 2008; 122: 213–4; author reply 14–5.
58. Chun R, Kirkpatrick AW, Sirois M, Sargasyn AE, Melton S, Hamilton DR, Dulchavsky S. Where's the tube? Evaluation of

hand-held ultrasound in confirming endotracheal tube placement. Prehosp Disaster Med 2004; 19: 366–9.

59. Blaivas M, Tsung JW. Point-of-care sonographic detection of left endobronchial main stem intubation and obstruction versus endotracheal intubation. J Ultrasound Med 2008; 27: 785–9.

60. Weaver B, Lyon M, Blaivas M. Confirmation of endotracheal tube placement after intubation using the ultrasound sliding lung sign. Acad Emerg Med 2006; 13: 239–44.

61. Kerrey BT, Geis GL, Quinn AM, Hornung RW, Ruddy RM. A prospective comparison of diaphragmatic ultrasound and chest radiography to determine endotracheal tube position in a pediatric emergency department. Pediatrics 2009; 123: e1039–44.

62. Park SC, Ryu JH, Yeom SR, Jeong JW, Cho SJ. Confirmation of endotracheal intubation by combined ultrasonographic methods in the Emergency Department. Emerg Med Australas 2009; 21: 293–7.

63. Hoffmann B, Gullett JP. Emergency ultrasound for the detection of esophageal intubation. Acad Emerg Med 2010; 17: 464–5.

64. Hatfield A, Bodenham A. Ultrasound: an emerging role in anaesthesia and intensive care. Br J Anaesth 1999; 83: 789–800.

65. Göksu E, Sayraç V, Oktay C, Kartal M, Akcimen M. How stylet use can effect confirmation of endotracheal tube position using ultrasound. Am J Emerg Med 2010; 28: 32–6.

66. Marciniak B, Fayoux P, Hébrard A, Krivosic-Horber R, Engelhardt T, Bissonnette B. Airway management in children: ultrasonography assessment of tracheal intubation in real time? Anesth Analg 2009; 108: 461–5.

67. Sustić A, Protić A, Cicvarić T, Zupan Z. The addition of a brief ultrasound examination to clinical assessment increases the ability to confirm placement of double-lumen endotracheal tubes. J Clin Anesth 2010; 22: 246–9.

68. Emshoff R, Bertram S, Kreczy A. Topographic variations in anatomical structures of the anterior neck of children: an ultrasonographic study. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 1999; 87: 429–36.

69. Hatfield A, Bodenham A. Portable ultrasonic scanning of the anterior neck before percutaneous dilatational tracheostomy. Anaesthesia 1999; 54: 660–3.

70. Sustić A, Kovac D, Zgaljardić Z, Zupan Z, Krstulović B. Ultrasound-guided percutaneous dilatational tracheostomy: a safe method to avoid cranial misplacement of the tracheostomy tube. Intensive Care Med 2000; 26: 1379–81.

71. Sustić A, Zupan Z, Antoncić I. Ultrasound-guided percutaneous dilatational tracheostomy with laryngeal mask airway control in a morbidly obese patient. J Clin Anesth 2004; 16: 121–3.

72. Muhammad JK, Patton DW, Evans RM, Major E. Percutaneous dilatational tracheostomy under ultrasound guidance. Br J Oral Maxillofac Surg 1999; 37: 309–11.

73. McCormick B, Manara AR. Mortality from percutaneous dilatational tracheostomy. A report of three cases. Anaesthesia 2005; 60: 490–5.

74. Reilly PM, Sing RF, Giberson FA, Anderson HL, Rotondo MF, Tinkoff GH, Schwab CW. Hypercarbia during tracheostomy: a comparison of percutaneous endoscopic, percutaneous Doppler, and standard surgical tracheostomy. Intensive Care Med 1997; 23: 859–64.

75. Kollig E, Heydenreich U, Roetman B, Hopf F, Muhr G. Ultrasound and bronchoscopic controlled percutaneous tracheostomy on trauma ICU. Injury 2000; 31: 663–8.

76. Kleine-Brueggeney M, Greif R, Ross S, Eichenberger U, Moriggl B, Arnold A, Luyet C. Ultrasound-guided percutaneous tracheal puncture: a computer-tomographic controlled study in cadavers. Br J Anaesth 2011; 106: 738–42.

77. Rajajee V, Fletcher JJ, Rochlen LR, Jacobs TL. Real-time ultrasound-guided percutaneous dilatational tracheostomy: a feasibility study. Crit Care 2011; 15: R67.

78. Vigneau C, Baudel JL, Guidet B, Offenstadt G, Maury E. Sonography as an alternative to radiography for nasogastric feeding tube location. Intensive Care Med 2005; 31: 1570–2.

79. Lock G, Reng M, Messman H, Grüne S, Schölmerich J, Holstege A. Inflation and positioning of the gastric balloon of a Sengstaken–Blakemore tube under ultrasonographic control. Gastrointest Endosc 1997; 45: 538.

80. Zhang M, Liu ZH, Yang JX, Gan JX, Xu SW, You XD, Jiang GY. Rapid detection of pneumothorax by ultrasonography in patients with multiple trauma. Crit Care 2006; 10: R112.

81. Peris A, Tutino L, Zagli G, Batacchi S, Cianchi G, Spina R, Bonizzoli M, Migliaccio L, Perretta L, Bartolini M, Ban K, Balik M. The use of point-of-care bedside lung ultrasound significantly reduces the number of radiographs and computed tomography scans in critically ill patients. Anesth Analg 2010; 111: 687–92.

82. Ding LW, Wang HC, Wu HD, Chang CJ, Yang PC. Laryngeal ultrasound: a useful method in predicting post-extubation stridor. A pilot study. Eur Respir J 2006; 27: 384–9.

83. Udy A, Senthuran S, Lipman J. Airway obstruction due to a pre-vertebral haematoma following difficult central line insertion – implications for ultrasound guidance and review of the literature. Anaesth Intensive Care 2009; 37: 309–13.

84. Arens C, Glanz H. Endoscopic high-frequency ultrasound of the larynx. Eur Arch Otorhinolaryngol 1999; 256: 316–22.

85. Arens C, Weigt J, Schumacher J, Kraft M. [Ultrasound of the larynx, hypopharynx and upper esophagus]. HNO 2011; 59: 145–54.

86. Doelken P, Strange C. Chest ultrasound for "Dummies". Chest 2003; 123: 332–3.

87. Lyon M, Walton P, Bhalla V, Shiver SA. Ultrasound detection of the sliding lung sign by prehospital critical care providers. Am J Emerg Med [Epub ahead of print].

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