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FULL PAPER

Multiplanar 3D ultrasound imaging to assess the anatomy of the upper airway and measure the subglottic and tracheal diameters in adults

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Objective: To evaluate the feasibility of using three-dimensional (3D) ultrasound to assess the anatomy of the airway.

Methods: 11 young volunteers were recruited for 3D ultrasound and MRI of the airway. 3D ultrasound data were obtained from the level of the true vocal cords, cricoid cartilage and upper trachea. Multiplanar 3D ultrasound images were rendered and compared visually with corresponding MRI and cadaver anatomical sections. The anteroposterior (AP) and transverse diameter of the subglottic space and transverse diameter of the upper trachea were also measured in the 3D ultrasound and MR images and compared.

Results: The airway anatomy was clearly delineated in the multiplanar 3D ultrasound images. It was also possible to identify the cricothyroid junction, and a simple method to measure the AP diameter of the subglottic space using this landmark is described. We were also able to

accurately measure the transverse diameter of the upper trachea, but the transverse diameter of the subglottic space was overestimated using ultrasound. There was a strong correlation for the AP diameter measurement ($r=0.94$, $p<0.05$) and moderate correlation for the transverse diameter measurement ($r=0.82$, $p=0.002$) of the subglottic space, and a strong correlation for the transverse diameter measurement ($r=0.91$, $p<0.05$) of the upper trachea, in the ultrasound and MR images.

Conclusion: The anatomy of the adult airway can be assessed using 3D ultrasound. It can also be used to accurately measure the AP diameter of the subglottic space and the transverse diameter of the upper trachea.

Advances in knowledge: This is the first report to describe the use of 3D ultrasound to evaluate the anatomy of the upper airway and accurately measure the AP diameter of the subglottic space and the transverse diameter of the upper trachea.

Ultrasound imaging of the airway has been described [1–6], but the majority of the published data involve the use of two-dimensional (2D) ultrasound, which allows examination of the airway in only the transverse or sagittal axis [2,7,8]. There is also a paucity of data correlating the sonoanatomy of the airway [2,7] with an alternative imaging modality [2]. Three-dimensional (3D) ultrasound imaging is currently available and provides simultaneous images of an area of interest (volume) in multiple orthogonal (perpendicular) planes [9]. Preliminary experience with 3D ultrasound suggests that the spatial anatomical information obtained is more detailed [9] than with 2D ultrasound, and the same may apply for imaging of the airway. Currently, there are no published data on 3D ultrasound imaging of the airway. The aim of this pilot study was to evaluate the feasibility of using

3D ultrasound to delineate the anatomy of the upper airway and correlate the sonoanatomy with cadaver anatomical sections and volunteer MR images of the airway. A secondary objective was to measure the subglottic and tracheal diameters in the multiplanar 3D ultrasound images.

MATERIALS AND METHODS

After Research Ethics Committee approval (The Joint Chinese University of Hong Kong—New Territories East Cluster Research Ethics Committee, Hong Kong, China; approval number CRE-2011.248) and written informed consent, 11 healthy young adult volunteers were recruited. Each volunteer underwent 3D ultrasound and MRI of the upper airway, which was performed by two independent operators, on separate occasions. Volunteers with a body

mass index (BMI) of $>35 \text{ kg m}^{-2}$, pre-existing laryngeal pathology, history of airway surgery and contraindication to MRI were excluded from the study.

3D ultrasound equipment and 2D scout scans

All the ultrasound scans were performed by a single investigator (anesthesiologist), who was experienced in 3D ultrasound imaging [9], with the volunteer lying comfortably on a bed and with the head and neck placed in the “sniffing the morning air” position (Figure 1). A Philips iU22 ultrasound system (Philips Healthcare, Andover, MA) with still image and video recording capabilities and a high frequency (VL13, 13–5 MHz), integrated volume linear array transducer (Philips Healthcare) were used for the scan (Figure 1). Since the quality of a 3D ultrasound image is dependent on the quality of the acquired 2D images, a transverse 2D ultrasound scan of the airway (scout scan) was initially performed over the true vocal cords (true VCs), and the images were optimised before the 3D data sets were acquired. The true VCs were identified by asking the volunteer to phonate by saying the words “eee-eee or aaa-aaa” and observing oscillation and movement towards the midline of the true VC in the 2D image [7].

3D volumetric ultrasound scan and image processing

3D volume data were then acquired from the level of the true VC, and 2–3 cm cranial and caudal to this site. Data at each site were acquired with the transverse scan plane as the data acquisition plane, the sweep angle set to 30° and with the volunteer's breath held in inspiration. Three data sets (volumes) were acquired at each site in every volunteer and stored in digital imaging and communications in medicine format in the ultrasound system for retrospective rendering and display. The stored data were transferred from the ultrasound system to a personal

computer, and QLAB (Philips Healthcare) software was used to render and display the acquired data in the multiplanar view (Figures 2–5). A three-image screen format was used for the multiplanar display in which Image 1 (top left) was the transverse plane image, Image 2 (top right) was the sagittal plane image and Image 3 (bottom left) was the coronal plane image. In every multiplanar display, the intersection of the three orthogonal planes was represented by a “reference marker” that was seen as a “cross-hair” in the ultrasound images (Figures 2–5). This is also a reference point that represents the same anatomical location in all the three ultrasound images. The reference marker was used to navigate through the acquired 3D volumes, and multiplanar images were rendered from the level of the false VC (Figure 2), true VC (Figure 3), cricoid cartilage (CC) (Figure 4) and upper trachea (Figure 5).

MRI of the airway

MRI of the airway (neck) was performed with the volunteer lying supine and with the head in the neutral position. A Philips Achieva 3T MRI system (Philips Healthcare, Best, Netherlands) with a neurovascular coil was used for the MRI. A standard T_1 weighted spin echo sequence was used for the study. Data acquisitions were initially performed in the sagittal and coronal planes to generate images of the airway in the transverse plane (sectional thickness 4 mm).

Gross anatomical sections of the airway

Cadaver anatomical sections of the airway were rendered from the Visible Human Project® male data set. The java applet in the Visible Human Server at Ecole Polytechnique Fédérale de Lausanne (EPLF) was used to navigate through the Visible Human Project data set and extract transverse anatomical sections from the levels of the false VC (Figure 6c), true VC (Figure 7c), upper part of the CC (Figure 8c) and upper trachea (Figure 9c). Coronal anatomical section of the upper airway was also

Figure 1. (a) The three-dimensional (3D) ultrasound system (Philips iU22; Philips Healthcare, Andover, MA), (b) integrated volume linear transducer (VL13-5, 13–5 MHz) and (c) position of the volunteer used for the 3D volumetric ultrasound scan of the airway. Reproduced with permission from www.aic.cuhk.edu.hk/usgraweb.

Figure 2. A multiplanar three-dimensional view of the upper airway with the “reference marker” placed at the level of the false vocal cords (FVCs). Note the hypoechoic thyroid (TC, thyroid cartilage) and cricoid (CC, cricoid cartilage) cartilages (a) and the hyperechoic cricothyroid membrane (CTM) between the TC and the CC (b). The air-mucosal interface (AMI) is also seen underlying the CTM. The coronal relation of the TC, FVC, true vocal cords (TVCs), paraglottic space (PGS), laryngeal ventricle (LV), subglottic space and CC is clearly delineated in the coronal view (c). SM, strap muscles; PES, pre-epiglottic space. Reproduced with permission from www.aic.cuhk.edu.hk/usgraweb.

Figure 3. A multiplanar three-dimensional view of the airway with the “reference marker” placed at the level of the true vocal cords (TVCs). Note the hypoechoic TVC posterior to the thyroid cartilage (TC) in the transverse axis view. SM, strap muscles; AC, arytenoid cartilage; PES, pre-epiglottic space; FVC, false vocal cords; LV, laryngeal ventricle and CC, cricoid cartilage. Reproduced with permission from www.aic.cuhk.edu.hk/usgraweb.

Figure 4. A multiplanar three-dimensional view of the airway with the “reference marker” placed at the level of the cricoid cartilage (CC). Note that the CC is “arched shaped” in the transverse view and “elliptical shaped” in the coronal view. Since the CC is shaped like a “signet ring”, the anterior wall of the CC may appear incomplete on a transverse sonogram and only the cricothyroid membrane (CTM) and the underlying air-mucosal interface (white arrowheads in the sagittal sonogram) is seen anteriorly. SM, strap muscles; TG, thyroid gland; TC, thyroid cartilage; TR, trachea; CTJ, cricothyroid junction. Reproduced with permission from www.aic.cuhk.edu.hk/usgraweb.

Figure 5. A multiplanar three-dimensional view of the airway with the “reference marker” placed at the level of the upper trachea (TR). Unlike at the level of the cricoid cartilage (CC), the isthmus of the thyroid gland (TG) lies anterior to the upper trachea. The tracheal rings appear like a “string of beads” on the sagittal sonogram. SM, strap muscles; CA, carotid artery; CO, cervical oesophagus. Reproduced with permission from www.aic.cuhk.edu.hk/usgraweb.

Figure 6. Correlative anatomy of the airway at the level of the false vocal cords (FVCs) as seen in a transverse sonogram (a), transverse MR image (b) and a representative anatomical section from the Visible Human Project® (cadaver, c). **Figure 6d** is an anatomical illustration from the same level. SM, strap muscles; TC, thyroid cartilage; PES, pre-epiglottic space; PGS, paraglottic space and PPW, posterior pharyngeal wall. The anatomical sections are courtesy of the Visible Human Server at EPLF, Visible Human Visualization Software: <http://visiblehuman.epfl.ch>, and Gold Standard Multimedia: www.gsm.org. The anatomical illustration in (d) is modified with permission from Amirsys Inc. and was originally published in [10].

acquired (**Figure 10c**). These anatomical sections were used to define the sonoanatomy of the upper airway in the 3D ultrasound images.

Anatomical correlation

The anatomy of the upper airway in the 3D ultrasound images were defined by visually comparing them with corresponding cadaver anatomical sections and MR images (**Figures 6–10**) by an anaesthesiologist and a radiologist together. Descriptive findings are presented.

Subglottic and tracheal diameter measurements

Anteroposterior (AP) and transverse diameter of the subglottic space and upper trachea were measured in the ultrasound and MR images. The measurements in the ultrasound images were performed by the principle investigator while those in the MR images were performed by a radiologist. Both observers were mutually blind to each other's measurements. With both imaging modalities, the transverse diameter of the subglottic space was measured at the upper part of the cricoid cartilage because it

is narrower than that in the lower part [11,12]. With the MR images, the AP diameter of the subglottic space was also measured at the upper part of the CC, whereas the AP and transverse diameter of the trachea was measured at the upper trachea. Since air-column artefacts obscured the posterior wall of the subglottic space in the ultrasound image, a horizontal line connecting the cricothyroid junction (CT), **Figure 8**, *i.e.* the articulation between the inferior cornu of the thyroid and CC, on either side, was used to estimate the location of the posterior wall for AP diameter measurement (**Figures 11 and 12**). The transverse diameter of the subglottic space was measured as the distance between the inner walls of the CC (upper part) in the coronal ultrasound image (**Figure 12**). Also, because the posterior wall of the upper trachea was obscured by air-column and reverberation artefacts, only the transverse diameter of the trachea was measured in the ultrasound images.

STATISTICS

The data were analysed using SPSS® for windows (v. 18, SPSS, Inc., Chicago, IL). Data are presented as mean $\pm$ standard deviation

Figure 7. Correlative anatomy of the airway at the level of the true vocal cords (TVC) as seen in a transverse sonogram (a), transverse MR image (b) and a representative anatomical section from the Visible Human Project® (cadaver, c). Figure 7d is an anatomical illustration from the same level. SM, strap muscles; TC, thyroid cartilage; PGS, paraglottic space; AC, arytenoid cartilage; CC, cricoid cartilage (quadrate lamina); TAG, thyro-arytenoid gap; VM, vocalis muscle. The anatomical sections are courtesy of the Visible Human Server at EPLF, Visible Human Visualization Software: <http://visiblehuman.epfl.ch>, and Gold Standard Multimedia: www.gsm.org. The anatomical illustration in (d) is modified with permission from Amirsys Inc. and was originally published in [10].

unless otherwise stated. The Bland–Altman method (Figure 13) and linear regression (Figure 14) were used to compare the measurements made by the two methods. The paired *t*-test was used to compare the difference in the AP and transverse diameter measurements made in the ultrasound and MR images. A *p*-value of <0.05 was considered statistically significant.

RESULTS

3D ultrasound and MRI examination of the upper airway was successfully performed on all the 11 volunteers (6 females, 5 males, aged 25 ± 4.5 years) studied. Cadaver anatomical sections of the airway were also successfully rendered from the Visible Human Project male data set. Multiplanar 3D ultrasound images of the upper airway from the levels of the false VC (Figure 2), true VC (Figure 3), CC (Figure 4) and upper trachea (Figure 5) were also rendered from the acquired 3D volumes in all the volunteers studied. The airway anatomy was clearly delineated in the multiplanar 3D ultrasound images and they were visually confirmed and correlated with that in the corresponding cadaver anatomical sections and MRI images (Figures 6–10).

In the median sagittal sonogram, the CC was seen as a rounded hypoechoic structure between the thyroid cartilage (TC) and trachea (Figures 2b, 3b and 4b). The cricothyroid membrane (CTM) appeared as a hyperechoic band between the caudal border of the TC and the cranial border of the CC (Figures 2b, 3b and 4b). The tracheal rings were also hypoechoic and resembled a “string of beads” [7] on the sagittal sonogram (Figure 5b). The interface between the mucosa lining the upper airway and the intraluminal air (A–M interface) produced a bright linear hyperechoic echo [7], in relation to the anterior aspect of the TC, CTM, CC and trachea (Figures 2–5). The epiglottis was visualised as an elongated hypoechoic structure that extended in a cranioposterior direction from the TC (Figures 2b and 3b). The pre-epiglottic space, which is filled with fat, appeared hyperechoic (Figures 2b and 3b). Intraluminal air produced air-column and reverberation artefacts, which prevented visualisation of the posterior wall of the pharynx, TC, CC and trachea in the sagittal sonograms. Multiple hyperechoic horizontal echoes, which at first appeared like the posterior wall of the trachea, was seen in the sagittal sonogram

Figure 8. Correlative anatomy of the airway at the level of the cricoid cartilage (CC) as seen in a transverse sonogram (a), a transverse MR image (b) and a representative anatomical section from the Visible Human Project® (cadaver, c). **Figure 8d** is an anatomical illustration from the same level. The cricothyroid junction (CTJ) as seen in a transverse sonogram (a), transverse MR image (b) and a representative anatomical section from the Visible Human Project (cadaver, c). Note that a horizontal line connecting the CTJ on either side approximates to where the posterior wall of the cricoid cartilage (CC, subglottic space) is located. TG, thyroid gland. The anatomical sections are courtesy of the Visible Human Server at EPLF, Visible Human Visualization Software: <http://visiblehuman.epfl.ch>, and Gold Standard Multimedia: www.gsm.org. The anatomical illustration in (d) is modified with permission from Amirsys Inc. and was originally published in [10].

(Figure 5b), but tracheal AP diameter measurement in the sagittal sonograms using these hyperechoic lines did not correlate with that in the MR images (data not provided). Therefore, we believe that the posterior horizontal hyperechoic echoes seen in the sagittal sonogram of the trachea (Figure 5b) are reverberation artefact of the anterior A–M interface owing to the presence of submucosal air, analogous to the A-line artefacts of the pleura seen during lung ultrasound [13].

In the transverse sonograms, the TC, false VC, true VC, CC and trachea were visualised as one examined in a craniocaudal direction (Figures 2a, 3a, 4a and 5a). The TC was hypoechoic and seen as an inverted V-shaped structure (Figures 6 and 7), posterior to which the false VC (Figure 6a) and true VC (Figure 7a) were identified. The false VC appeared as two fleshy hyperechoic structures, one on either side of the midline (Figure 6a). The fat-filled paraglottic spaces were identified lateral to the false VC. Caudal to the false VC, the true VC was

visualised (Figure 7a). They were hypoechoic in appearance, triangular in shape and outlined medially by the hyperechoic vocal ligaments (Figure 7a). Posteriorly, the anterior surface of the posterior quadrangle lamina of the CC, outlines of the arytenoid cartilage and the cricoarytenoid articulation were also visualised in the transverse sonogram (Figure 7a). The CC was identified as an “inverted-U” or arched-shaped structure. The inner surface of the anterior wall of the CC was lined by the bright A–M interface (Figure 8a), and the two lobes of the thyroid gland were seen as a uniformly hyperechoic structure lateral to the CC (Figures 4a and 8a). The posterior wall of the CC was obscured by air-column and reverberation artefacts, but we could identify the CTJ (Figure 11) as a hypoechoic gap in the posterolateral wall of the CC on either side (Figure 8a). This was confirmed in the multiplanar 3D ultrasound images (Figure 11), MR images (Figure 8b) and cadaver anatomical sections (Figure 8c). A horizontal line connecting the CTJ on either side corresponded to where the posterior wall of the CC

Figure 9. Correlative anatomy of the airway at the level of the upper trachea (TR) as seen in a transverse sonogram (a), transverse MR image (b) and a representative anatomical section from the Visible Human Project® (cadaver, c). **Figure 9d** is an anatomical illustration from the same level. ScM, sternocleidomastoid muscle; TG, thyroid gland; TR, trachea; CA, carotid artery; CO, cervical oesophagus; LM, longus colli muscle; CA, carotid artery and IJV, internal jugular vein. The anatomical sections are courtesy of the Visible Human Server at EPLF, Visible Human Visualization Software: <http://visiblehuman.epfl.ch>, and Gold Standard Multimedia: www.gsm.org. The anatomical illustration in (d) is modified with permission from Amirsys Inc. and was originally published in [10].

Figure 10. Correlative anatomy of the airway as seen in a coronal sonogram (a), coronal MR image (b) and a representative coronal anatomical section from the Visible Human Project® (cadaver, c). TC, thyroid cartilage; TVC, true vocal cords; CC, cricoid cartilage; Tr, trachea; TG, thyroid gland; FVC, false vocal cords and LV, laryngeal ventricle. The anatomical sections are courtesy of the Visible Human Server at EPLF, Visible Human Visualization Software: <http://visiblehuman.epfl.ch>, and Gold Standard Multimedia: www.gsm.org.

Figure 11. A multiplanar three-dimensional view of the cricothyroid junction (CTJ, arrow). It represents the articulation between the inferior cornu (horn) of the thyroid cartilage and the cricoid cartilage. SM, strap muscle; CC, cricoid cartilage. Reproduced with permission from www.aic.cuhk.edu.hk/usgraweb.

was located in the MRI and anatomical sections (Figure 8) and was used to measure the AP diameter of the subglottic space (Figure 12). The trachea also appeared hypoechoic, was “U-shaped” and outlined by the bright A–M interface anteriorly, but unlike at the level of the CC, the thyroid isthmus was seen anterior to the trachea and the cervical oesophagus could also be identified posterolateral and to the left of the trachea.

The coronal sonograms provided a “birds-eye view” of the upper airway anatomy and the coronal relation of the TC,

false VC, laryngeal ventricle, true VC, subglottic space and CC were clearly delineated (Figures 2 and 3) and it mirrored that seen in the coronal MRI and cadaver anatomical section (Figure 10). The CC was seen as a pair of hyper-echoic and elliptical structures in the coronal sonograms (Figures 3c and 12).

The AP diameter of the subglottic space was significantly larger than the transverse diameter in both the ultrasound (AP, 1.72 ± 0.23 cm vs transverse, 1.54 ± 0.23 cm, $p=0.004$) and MR (AP,

Figure 12. Figure shows how the anteroposterior (AP) and transverse diameters of the airway at the level of the cricoid cartilage (subglottic space) were measured in the ultrasound and MR images. A horizontal line connecting the cricothyroid junction (CTJ), in the transverse sonogram, on either side was used to locate the position of the posterior wall of the cricoid cartilage (CC, a) for the AP diameter measurement (a). The transverse diameter was measured as the distance between the inner walls of the upper parts of the CC in the coronal sonogram (c). Figure 12d illustrates how the corresponding measurements were made in the MR images. Reproduced with permission from www.aic.cuhk.edu.hk/usgraweb.

Figure 13. Bland–Altman analysis of the ultrasound and MRI measurements of the anteroposterior (a) and transverse diameter (b) of the subglottic space and the transverse diameter of the upper trachea (c). The solid line represents the bias (the average difference between paired measurements) and the dotted lines represent the limits of agreement (bias $\pm$ 1.96 standard deviation).

1.78 $\pm$ 0.27 vs transverse 1.38 $\pm$ 0.21 cm, $p<0.0005$) images. The transverse diameter of the upper trachea as measured in the ultrasound (1.50 $\pm$ 0.23 cm) and MR (1.47 $\pm$ 0.20 cm) images were comparable ($p=0.22$). Bland–Altman analysis showed that there was no bias in the sonographic measurements of the AP diameter of the subglottic space (mean difference = -0.06 cm, precision = 0.02, limits of agreement = -0.125–0.007, Figure 13a) and transverse diameter of the trachea (mean difference = 0.04 cm, precision = 0.02, limits of agreement = -0.02–0.10, Figure 13c), but the transverse diameter of the subglottic space was overestimated in the ultrasound images (mean difference = 0.16 cm, precision = 0.08 cm, limits of agreement = 0.07–0.25, Figure 13b). There was also a strong correlation for the AP diameter measurement ($n=11$, $r=0.94$, $p<0.05$, Figure 14a) and a moderate correlation for the transverse diameter measurement ($n=11$, $r=0.82$, $p=0.002$, Figure 14b) of the subglottic space in the ultrasound and MR images. There was also a strong correlation for the transverse diameter measurement ($n=11$, $r=0.91$, $p<0.05$, Figure 14c) of the trachea in the ultrasound and MR images.

DISCUSSION

We have demonstrated that multiplanar 3D ultrasound imaging can be used to reliably study the anatomy of the upper airway. The anatomical information obtained with 3D ultrasound is more detailed than what is typically seen with 2D ultrasound and compares well with MRI. We were also able to accurately measure the AP diameter of the subglottic space and the transverse diameter of the upper trachea, but the transverse diameter of the subglottic space was overestimated using ultrasound. This is the first report to describe the use of 3D ultrasound to evaluate the anatomy of the upper airway and measure the subglottic and tracheal diameters.

Under the conditions of this study, we were able to visualise the majority of the laryngeal structures from the level of the false VC to the upper trachea in the multiplanar 3D ultrasound images. The structures that were visualised correlated well with that in the cadaver anatomical sections and MR images from the volunteers. There are no comparable data in the literature but our

Figure 14. Linear regression of the anteroposterior (a) and transverse (b) diameter of the subglottic space, and the transverse diameter of the upper trachea (c) measured using ultrasound and MRI, with line of equality.

observations are in agreement with Singh et al [7], who described the detailed sonoanatomy of the upper airway using 2D ultrasound [7]. More recently, Prasad et al [2] demonstrated that the anatomical structures visualised with 2D ultrasound correlates well with those in CT images. Our observation that this is also true with MRI provides further evidence that ultrasound is reliable for imaging the airway despite the artefacts produced by air within the airway lumen.

In the multiplanar display, it was possible to simultaneously visualise the anatomy of the upper airway in the transverse, sagittal and coronal axes. Currently, it is possible to obtain high-resolution 2D ultrasound images of the airway in the transverse and sagittal axes [2,7,8], by rotating the transducer through 90° , but it is not possible to obtain coronal views of the airway using traditional 2D ultrasound equipment. The coronal view displays the anatomy as though one were looking down onto the area of interest, *i.e.* analogous to a “birds-eye-view”. In this study, the coronal relationship of the false VC, laryngeal ventricle, true VC,

subglottic space, CC and trachea, which was not evident in 2D ultrasound images, was clearly delineated. The improved spatial awareness of the upper airway anatomy with multiplanar 3D ultrasound imaging may be considered as one of its advantages. The multiplanar views also provided additional anatomical information, such as being able to locate the CTJ, which was not identified in the 2D ultrasound images. Using the CTJ as a landmark, we have described a simple method of accurately measuring the AP diameter of the subglottic space using ultrasound.

The AP diameter of the subglottic space was larger than the transverse diameter. This is in agreement with published data [3,11] showing that the subglottic space is not cylindrical [3], and there are large differences in laryngeal dimensions within the population [11]. We were also able to accurately measure the AP diameter of the subglottic space and the transverse diameter of the upper trachea using ultrasound. There are no comparable data on the use of ultrasound to measure the AP diameter of the

subglottic space because air-column and reverberation artefacts preclude identification of the posterior wall of the airway. This is the first report to describe the use of ultrasound to measure the AP diameter of the subglottic space. The method we have described is indirect and utilises a horizontal line connecting the CTJ on either side, as a surrogate, to locate the posterior wall of the cricoid cartilage in the ultrasound images. Being able to non-invasively and accurately measure the AP diameter of the subglottic space and the transverse diameter of the upper trachea using ultrasound may have potential clinical applications and deserves further investigation in the future.

The transverse diameter of the subglottic space was overestimated using ultrasound. Our results contradict those of Lakhal et al [3] who reported that ultrasound accurately measures the transverse diameter of the subglottic space, but are in agreement with those of Husein et al [14] who also found that ultrasound is inaccurate (underestimates) in measuring the transverse diameter of the subglottic space in children. The reason for this difference may be multifactorial but the method used to locate the subglottic space by Lakhal et al [3], *i.e.* identifying the air-column width at the level of the cricoid cartilage, may be subject to error because the subglottic air-mucosal interface rarely produces a sharp outline (laterally) in a transverse sonogram to allow accurate identification. By contrast, we measured the transverse diameter of the subglottic space in the coronal image of the multiplanar view because the inner wall of the cricoid cartilage was clearly delineated in all volunteers studied. Future research should clarify this controversy.

Currently, there is a paucity of data on the clinical utility of ultrasound imaging of the airway and in particular the larynx. This may be because laryngoscopy, CT and MRI are considered the gold standard for evaluating the larynx. However, laryngoscopy is an invasive procedure, whereas CT and MRI cannot be performed at the point of care and necessitates transfer of the patients to the radiology suite. CT and MRI may also necessitate sedation and or immobilisation of the patient. Ultrasound imaging is safe, non-invasive, can be quickly performed, provides real-time images and does not carry risk of exposure to radiation, and more importantly can be performed on an awake patient at the bedside. A review of the literature shows that 2D ultrasound has been used to

locate the cricothyroid membrane [15], predict the size of an endotracheal tube in children [16], locate the trachea before surgical tracheostomy [17], guide percutaneous tracheal puncture [18], study VC function (mobility) [19], diagnose acute epiglottitis [6], evaluate recurrent laryngeal papillomatosis [20] and predict post-extubation stridor [5]. 3D ultrasound is also non-invasive, and as demonstrated in this study, the anatomical information obtained is more detailed than with 2D ultrasound and also compares well with MRI. Acquisition of the 3D volumes also takes less than a minute and the stored data sets can be easily rendered in the ultrasound system (in-cart) or on a personal computer (off-cart) using a rendering software, and displayed in different formats. The anatomy of the airway can also be viewed from various angles. All these features make 3D ultrasound an attractive alternative for imaging the airway at the point of care, and future research in this area is warranted.

A limitation of our study is that the volunteers recruited were young and had normal BMIs. Therefore, the results of this study may not apply to the elderly and the obese. Also the retrospective rendering of the acquired 3D data sets may be considered a disadvantage. Real-time 3D (4D) imaging is currently available but is not strictly necessary for assessment of the airway anatomy. Another potential disadvantage of 3D imaging is that acquisition and interpretation of images, without additional training, may be more complex than with 2D ultrasound imaging. 3D ultrasound systems are also significantly more expensive than 2D ultrasound systems.

In conclusion, we have demonstrated that 3D ultrasound imaging can be used to delineate the anatomy of the adult airway. The anatomical information obtained is more detailed than what is typically seen in 2D ultrasound images and compares well with MRI. It can also be used to accurately measure the anteroposterior diameter of the subglottic space and the transverse diameter of the upper trachea. Future research to evaluate the clinical utility of these findings is warranted.

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