Is it time to FONA friend? a mixed reality Front of Neck Access simulator

Abstract

Emergency cricothyroidotomy is a lifesaving but infrequently performed procedure for emergency airway difficulty. This is performed as the final 'rescue' step, after all non-invasive intubation techniques have failed. This time critical procedure must be performed with efficiency and proficiency. Such expertise is developed through experience however as this procedure is rarely encountered, these skills are taught through simulation.

Hence this research sought to develop a simulation for practise of front of neck access, that is easily accessible, cheap, and ethically sustainable that offers moderate realism. Hence a mixed reality cricothyroidotomy simulation was created, whereby a mobile application demonstrates the technical steps in CCT using augmented reality, then later records the participant performing the procedure on a 3D anatomically correct larynx model.

Though the technology is still experimental, the protype and pilot test have demonstrated positive results, with the majority of the participants agree that there should be increased frequency in training CCT and that this simulator is adequate for this task.

There is still scope for further development; the model can be modified to demonstrate the anatomical variations of gender and age as well as developing a new semi-rigid material for 3D printing that has greater similarity to cartilage. The application can be further enhanced by making the AR animation more streamline, the educational information more detailed and the feedback more intuitive. The advancement of technology will bring with it an abundance of new directions for this application and for medical education.

Keywords

Cricothyroidotomy, simulation, medical education, mixed reality, airway, FONA, front of neck access

Abbreviations: CCT cricothyroidotomy, FONA front of neck access, DAS difficult airway society, CT computer tomography.

1. Introduction

Cricothyroidotomy (CCT) is a low frequency, high intensity, life-saving procedure. It is indicated in the final step of the Difficult Airway Society (DAS) guidelines, known as a “Can’t intubate Can’t ventilate” scenario. It is also indicated as the primary airway management strategy when the oral route is inaccessible with associated emergent airway compromise, such as severe head and neck trauma, haemorrhage or inhalation injury (Helm, Gries, and Mutzbauer 2005; Erlandson et al. 1989). As the name would suggest, a cricothyroidotomy involves the surgical insertion of an endotracheal tube or tracheostomy tube directly through the cricothyroid membrane to sit within the trachea and allow ventilation, bypassing the proximal obstruction.

An obstructed airway can rapidly lead to hypoxia and potentially death if the airway is not promptly secured. As CCT is the last resort in securing the airway, confidence, efficiency and technical knowledge are imperative, however, exposure to CCT is increasingly uncommon which can lead to skill degradation and reduced confidence. To overcome this, as with many aspects of medical education, simulation has long been used as an adjunct to clinical experience. Simulation, in its many forms, has benefits in alleviating inconsistencies between trainee experiences by providing a safe and reproducible learning environment for practitioners to learn and undertake deliberate practise of their technical and non-technical skills (McGaghie et al. 2009). Many studies have demonstrated the benefits of simulators for medical education with greater satisfaction rates and higher examination results as well as allowing for quantitative assessments of competencies and feedback, within a safe and standardised environment (Ten Eyck, Tews, and Ballester 2009; Kulkarni 2019; Krishnan, Keloth, and Ubedulla 2017). Although there is proven benefit in using simulations, barriers are present with regards to access, time constraints and incentives (Walker et al. 2020; Thinggaard 2017). It was with this in mind that the current research was developed; to produce an easily accessible, ethically compliant, low-cost cricothyroidotomy skill trainer to allow deliberate practice of front of neck access (FONA).

2. Challenges for medical educators and FONA

2.1 Morphometric differences

The cricothyroid ligament (CTL) is the recommended access point for performing emergency FONA. Anatomically this is located at the distal aspect of the thyroid cartilage in a space, known as the cricothyroid interval, before reaching the signet-ring shaped cricoid cartilage at the level of C6. Externally this is palpated by tracing a finger inferiorly in the midline along the body of the thyroid cartilage until the concavity of the cricothyroid interval is felt. Unfortunately, anatomy in practice is not so simple. Palpation of the anatomy can also be hindered by body habitus, neck position such as flexion or extension or indeed change of anatomic planes by infection or trauma. Further to this there are more innate difficulties with a significant variation present between gender, age, and race. Studies have demonstrated that the anterior height of the thyroid cartilage was approximately 20.77 ±2.7 and 15.39±2.3mm for male and females respectively. Similarly, studies have demonstrated that there is a significant variation in cricoid diameter between male and female cadavers (15.0mm-11.6mm), between races, as well as individuals within each category. In addition, there is gender variation in the vertical distance of the cricothyroid membrane, mean 7.6mm-6.4mm respectively. This is clinically important in choosing the size of the tracheal tube, too small and there is inadequate ventilation, too large and there is difficulty in accessing the trachea and can later lead to mucosal pressure necrosis (Ajmani 1990; Randestad, Lindholm, and Fabian 2000; Jotz et al. 2014).

Though this study primarily focuses on the adult airway it is important to be aware that the growing, paediatric airway presents great difficulty that extends beyond just size. Studies have shown the cricothyroid ligament is inaccurately identified in all ages of children, with no improvement with repeated attempts (Fennessy et al. 2019). Presumably this is why the recommendation in children less than eight years old, in a “cannot intubate and cannot oxygenate” (CICO) scenario, in the absence of an otolaryngologist, is to perform a needle cricothyroidotomy, minimising tissue destruction and complications of failed CTL identification (Black et al., 2015).

2.2 Urgency of the situation

A cannot intubate cannot oxygenate (CICO) scenario is a life-threatening emergency with potential rapid deterioration and mortality hence requires urgent evaluation and management. It is deemed a CICO scenario when all other intubation techniques have failed, and there is no way to ventilate a patient. This can result from an acute upper airway obstruction or from an unanticipated difficult airway, either aetiology is a time limiting emergency.

Upper airway obstruction refers to the obstruction, either partial or complete, of any region from the oro- or naso- pharynx to the subglottic region which can compromise ventilation and subsequent oxygenation, of the patient (Eskander, de Almeida, and Irish 2019). Due to their high metabolic rate, neurones are particularly sensitive to this lack of oxygen, unconsciousness often occurs at approximately 15 seconds and anoxic-cerebral ischaemia can occur in 5 minutes or less and death can follow shortly after (Fugate and Wijdicks, 2016). This gives very little time to attempt endotracheal intubation, face-mask ventilation or placement of a supraglottic airway device (SAD); even in the presence of temporizing methods such as supplemental oxygen, heliox, nebulised adrenaline and steroids. This scenario is high intensity and can be very distressing to both patient and practitioner. Time allowing, a formal surgical tracheostomy would be optimal way to secure the obstructed airway, however when CICO is declared in an unstable patient the rescue procedure to re-establish oxygenation is cricothyroidotomy, a 'definitive' airway can be secured subsequently.

2.3 Infrequency and lack exposure

Over the years intubation adjuncts such as cricoid pressure, external laryngeal manipulation, better neuromuscular relaxants and use of a Bougie have improved first pass tracheal intubation. With the addition of improved visualisation techniques such as video laryngoscopy and nasal intubation, first pass tracheal intubation is documented to be between 71.5-85% depending on operator and stylet usage (Myatra, Sakles, and Roca 2021). The UK Difficult Airway Society (DAS) have published guidance in the event of an unanticipated difficult intubation. These guidelines, which include: 3(+1) attempts at video/direct laryngoscopy by experienced anaesthetist, followed by a maximum of 3 attempts at SAD intubation and all other simple manoeuvres and devices i.e., face mask, to oxygenate the patient; prior to a declaration of CICO (DAS guideline 2015). Therefore, the CICO scenario is extremely rare with greater than three attempts are seen in only 0.8% of emergency intubations and only 0.3% require cricothyroidotomy (Bakhsh et al. 2021; Park, Zeng, and Brainard 2017). A UK study 'on the right Trach?' demonstrated that exposure to front of neck access for surgical trainees are limited as the majority of tracheostomies are performed percutaneously by intensivists within the intensive care unit (ITU). That is 70% of new tracheostomies are percutaneous, the remaining surgical tracheostomies 47% were performed by consultants and 41% by senior surgical trainees, suggesting early surgical trainees have little experience in performing even elective tracheostomies and one can presume less comfortable with the lesser performed cricothyroidotomy (Wilkinson et al., 2014).

2.4 Varying techniques

Cricothyroidotomy, i.e., creating a ventilation pathway through the cricothyroid membrane is performed in one of two ways: surgical method or needle ventilation. However, NAP4 audit offered key details highlighting the failings of the needle or cannula cricothyroidotomies with 58% of cannula cricothyroidotomies failing and required further rescue procedures (Cook et al., 2011). This may be due to the high pressures required to ventilate through either a narrow or wide bore cannula, in the absence of a jet ventilator this provides inadequate ventilation. Even in the presence of jet ventilation, air trapping can occur which again provides unsatisfactory ventilation over time (Scrase and Woollard 2006). Even though this technique is taught alongside surgical techniques in courses such as ATLS, ALS and CCRISP, there has been a move away from cannula ventilation which is corroborated by the DAS guidance advocating surgical techniques.

There is however no clear consensus on the surgical technique to be used which leads to dubiety in teaching. The main methods are puncture technique, using the Portex Crico Kit which utilises a needle, dilator and tracheostomy tube in a Seldinger method. The other methods are both scalpel techniques in which a scalpel is used to create an incision over the cricothyroid membrane; in the DAS technique they prioritise economy of movement, with a 90º rotation of the scalpel after puncture and use this as a guide to insert a Bougie though the membrane allowing the tracheostomy tube to pass over this into the trachea. The second scalpel technique, which is taught during ATLS, again uses a scalpel, however instead of a stab technique, a horizontal incision is made over the CTM, where tracheal dilators are inserted to open the incision and create passage for the tracheal tube. The scalpel techniques are preferred over the percutaneous technique due to the lower complication rate in inexperienced hands during an emergency (Helm et al. 2013; Helm, Gries, and Mutzbauer 2005). Both scalpel techniques are valid and correct and appears to be dependant on the course on which it is taught and the target audience i.e. anaesthetists versus surgeons, however a consensus should be sought to ensure there is no confusion during emergency situations.

2.5. Surgical training

2.5.1 Expertise

Given the high intensity of the “can’t intubate can’t oxygenate” scenario it would be appropriate for front of neck access to be gained by an “expert” in airway management. K Anders Ericsson defined an expert as someone “able to perform at virtually any time with relatively limited preparation”, meaning they should be aware of the anatomy and the procedure and any variation that should present (Ericsson KA 2008).

However educational theory indicates, that in the development of “expertise”; sustained and deliberate practise is necessary, with a reported 10,000 hours requirement (Ericsson, Krampe, and Tesch-Römer 1993; Ericsson 2015; Macnamara, Hambrick, and Oswald 2014). With this level of deliberate practice, performance has less variability, greater retention and adaptability when presented with unexpected variations (Magill and Anderson 2010). There are nine elements to deliberate practice (Barsness 2020):

1. Highly motivated learners
2. Well-defined learning objectives
3. Appropriate level of difficulty
4. Focused, repetitive practice
5. Rigorous measurements
6. Informative feedback
7. Monitoring, error correction and more deliberate practice
8. Performance evaluation towards mastery standards
9. Advancements towards the next task

The concept of motivation has been thoroughly studied, producing countless theories proposing to explain human motivation. Motivation in learning has been shown to be a predictor for academic success, persistence in study and well-being (Kusurkar et al., 2011). Common themes in most contemporary theories are the drive for competence, value of learning the task, attributions for the results (in terms of locus, stability and controllability), interactions between individuals and finally the learning context (Cook and Artino 2016). Medical practitioners are generally seen to be *motivated* learners given all the requirements and abilities for entry into medical school. Motivators for medical practitioners may be a complex interplay of intrinsic and extrinsic factors. Intrinsic motivation is built on the inherent needs of self-determination and competence allowing the practitioner to pursue learning for one's own interest, enjoyment or to feel related to significant players in their life. Extrinsic motivation makes a person pursue an activity for separable outcome e.g., to obtain a reward or avoid a loss (Kusurkar et al 2011).

Goal orientated *mastery* motivation theory proposes that through incremental learning and practise, one can become smarter or more skilled. Mastery learning compromise two core principles, firstly that all learners have the potential to achieve the same uniform performance goal. Secondly, that some learners take longer than others to achieve the uniform performance goal (Barsness 2020). In short, everyone one can attain similar proficiency standards if given enough time and practice. For cricothyroidotomy experience and practice does contribute to better success. Carvey et al demonstrated those with previous clinical experience in CCT had better success rates initially, however when repeating this simulation ten times the CCT times plateaued by the fourth attempt and success rates by the fifth, meaning uniform performance was achieved. Similar results have been found in other studies with five CCT performances being the key to improved performance (Carvey et al 2020, Buonopane et al. 2014, Qi et al., 2020).

Mastery learning is increasingly being introduced to the medical and surgical curricula, making redundant the adage of "see one, do one teach one" which, perhaps, erroneously assumes mastery of a skill in only a few attempts. This goes beyond simple skill or procedure repetition to gain competence in a skill. Instead, *mastery learning* focuses on incremental improvement, feedback and assessment against a fixed set of learning objectives until mastery standards are achieved.

2.5.2 Skill retention

In reaching mastery standards for surgical skills repetition is key, this allows for improved fluency and efficacy in movement, fewer mistakes, and better knowledge of the procedural steps. This repetition may improve short term performance and meeting assessment standards however this does not convey skill retention. Studies have demonstrated that skill performance, based on repetition, is subject to decay after 90days (Higgins, Madan, and Patel 2020). This indicates that these skills require regular practice and assessment to maintain mastery performance standards.

2.5.3 Surgical training program

In response to the 'Shape of training' report released in 2013, the Royal College of Surgeons England (RCSEng) and Health education England (HEE) introduced the Improving Surgical Training (IST) program. It targeted the dissatisfaction within surgical training that arose from the imbalance of service provision and training; trainees felt that there was lack of time for formal training, poor flexibility within the programme and greater production of inexperienced surgeons (Allum 2020).

Surgical training has been on of apprenticeship, whereby trainees perform complex operations under the tutelage of more experienced surgeons. Although there are benefits to this expert guidance, it understandably yields variable outcomes, with innate differences in tutors and teaching styles, inconsistent exposure to procedures and invariable differences between training centres. Therefore, IST is an innovative and evidence-based approach to surgical training that aimed at improving the surgical 'generalist' (Greenaway 2013). It brought about changes to training with 60% of the working week dedicated to formal training, training lists, clinics and greater input from mentors. Alongside this, a new simulation-based learning programme was advocated by the Chief Medical Officer in 2008; this included various simulations, mastery learning, skill acquisition through take-home laparoscopic box trainers and e-learning modules (Walker et al. 2020; Allum 2020; Donaldson 2009).

2.6 Simulations

2.6.1 Simulation for surgery

Surgical simulation can come in a variety of forms, from actors playing a role in a communication scenario to an animatronic patient with vital signs. They are used as artificial representations of real-world processes. Simulations are best suited to situations and skills that are high risk or rare (or combination of these) so that practice of these can be performed in an environment that allows for repeated controlled experience that is safe to the patient. Issenberg *et al* proposed features of a simulator for effective learning. Content validity is where the simulator undergoes expert assessment to determine its suitability as a teaching tool. Face validity is the assessment of realism that can provide context for learning (Issenberg et al. 2005). This is similar to a simulation's fidelity, where it is assessed for its perceived likeness to reality in terms of its visual, auditory and proprioceptive stimuli. Often high-fidelity simulators come with barriers such as substantial cost or accessibility issues e.g., cadaveric models. Reassuringly studies have demonstrated that in the case of skill learning, there is no significant difference in the learning outcomes when comparing high and low fidelity simulators (Massoth et al. 2019).

Another feature of an effective simulation is feedback, this allows the trainee to change and improve upon the skills learnt. This is against expert opinion either by way of a supervisor or against specific target markers within the simulation itself. The lack of feedback can be detrimental to the engagement of a trainee to the simulator, such as that found with laparoscopic box trainers, where incentivised practice and involvement in the curriculum was recommended (Walker et al. 2020; Nicholas et al. 2019)

2.6.2 technological improvements

Recently, with the exponential improvement of technology new simulators are being introduced using virtual or augmented reality, which offer immersive and dynamic experiences to the user. Virtual reality (VR) is a technology that uses the senses of the participant (sight, movement, and hearing) to fully immerse the trainee into a high-resolution synthetic environment. In contrast, augmented reality (AR) allows alteration of the real world, often by superimposing digital components into the real environment, in this way the participant can interact with both real and virtual elements (Moro et al. 2017).

These are being increasingly utilised within medical sciences and will likely continue with the improved availability and access to VR and AR on phones, tablets, or increasingly affordable headsets (Moro et al. 2017; Yoon et al. 2018). This has been pivotal in medical education particularly in the teaching of anatomy. These virtual 3D models give students the chance to develop the spatial awareness of anatomical structures, interact with them and assist in the comprehension of learning new anatomical contexts. It also acts as an adjunct to cadaveric teaching if this is scarcely available. Studies have demonstrated that these 3D constructs are more beneficial than traditional 2D textbook learning and can optimise distance learning (Moro et al.,2017).

These technologies have been increasingly adapted for surgical practice. They have had significant advances in pre-surgical planning, currently used frequently in procedures involving complex boney arrangements i.e., cranio-maxillofacial bones and complex hip bones. Neurosurgeons are making use of VR environments with haptic feedback in planning and practicing complex neurosurgical procedures (Kim et al., 2017). AR has shown its utility as an intraoperative guidance system, using image overlay taken from the patients CT/MRI images to demonstrate not normally visualised anatomy or present optimal surgical paths for the operator (Kim et al., 2017).

2.6.3 Current CCT simulators

There are many cricothyroidotomy simulators currently in practice. The gold standard for anatomic accuracy and tissue handling is cadaveric CCT practice, however, access to cadaveric dissection has cost, location and ethical barriers associated with it. To mitigate these difficulties ex-vivo animal models have been used instead with great results, most commonly porcine and ovine (fig 1b). However, there is still ethical considerations, anatomic variation, as well as the possibility of zoonotic diseases that create difficulties (Cheng et al. 2019; Deonarain et al. 2021; Soliman, Ianacone, and Isaacson 2018). With the compromise of tissue realism multiple silicon and plastic models exist (fig1c.), however these often have moderate cost, single-use skin, variable anatomic accuracy and are often limited to a departmental sim lab. Although tissue realism is helpful in performing CCT, studies have shown that low fidelity models such as fig.1(d) are an adequate teaching tool until automation in the task is acquired (Friedman et al. 2008; Aho et al. 2015).

Although for the improvement of dexterity and technical skill, simulators that allow for handheld instruments and palpation of the appropriate anatomy are the most beneficial. New technology such as the VAST-CCT simulator (figure 1a.) is offering excellent visual impact and teaching of the procedural steps and anatomy, however, the haptic stylus limits the user from proprioceptive stimulus lowering its content validity (Qi et al., 2020).

2.7 Our approach

With mastery learning in mind Using the information available it was clear that a method of allowing the deliberate practice of cricothyroidotomy is needed to ameliorate the lack of clinical exposure. This educational resource should have the trainees needs as the priority. These qualities include, easily accessible, reproducible, anatomically accurate, cheap, ethically sustainable and allows for feedback. Therefore, this research set about developing a mixed reality simulation using a physical anatomically accurate larynx model with an educational application, for phone or tablet, to teach the procedure and allow for feedback to be given.

3 Our work

3.1 Model development

To maintain anatomic accuracy, the 3D larynx model was created using DICOM data using patient CT scans. A female patient was felt to represent a moderate degree of difficulty due to the anatomic size variation between the genders. The dataset 'Eve' was provided as DICOM data from the Glasgow School of Art and was imported into 3D Slicer for segmentation. Initial attempts to improve segmentation outcomes using thresholding and Laplacian filters were unsuccessful due to the poor tissue differentiation between the cartilaginous skeleton of the larynx and the surrounding soft tissue. It was therefore segmented on a slice-by-slice basis with anatomic knowledge of the expected boundaries using the threshold limits of 25-1660 (fig 2).

This model was subsequently exported into 3Dstudio max as an .obj file, where it could be adjusted for better virtual use. Firstly the polygons were reduced from 47000 to 1648 firstly by using the ProOptimiser tool then later by manual retopology. Retopology also allowed completion of areas of soft tissue missed and small defects created from segmentation (fig 3).

This 3D model was saved in stl format and was now suitable for 3D printing. Discussions pertaining to the printing material led to great difficulty. Initially, it was proposed that this was printed from an aquagel or similar semi-rigid material to allow for similar tissue flexibility and appropriate extension of the cricothyroid interval for passage of an endotracheal tube during simulation. However, attaining these semi-rigid materials was difficult and so this has been cheaply printed using resin (fig 4.). This would allow for easier access to printing and upon discussion could potentially provide multiple models that could be taken home by trainees upon request or as part of training curricula. This was therefore printed in the anatomically accurate size as well as a scale increase of 1.5 to enable easier passage of an ET tube during the simulation, when there was no flexibility in the model.

3.2 Application development

The design of the application was intended to be simple and easy to interact with. Ideally the application would not impede the technical aspect of the procedure and so the UI and images are to minimally obstruct the scene and field of view of the trainee. The application design underwent dynamic changes during the development process. Initially, it was proposed that the application would place an augmented reality head and neck over the 3D printed model to allow for a simple reproducible simulation that could easily be accessed on any mobile device. The application was developed in Unity 3D engine, with the target image designed in Procreate (fig 7.). The development was attempted on multiple platforms including Vuforia, ARKit, ARCore, AR Foundation and XR Management Plugin. However, it was soon apparent when testing the prototype, on both IOS and Android systems, that mobile technology is still experimental even when using unity, macOS and Xcode upgrades. No processing system yielded a level of functionality to provide adequate hand occlusion to allow interaction with the 3D model under the superimposed augmented head (fig 8-9). This could be potentially dangerous as part of the procedure requires scalpel use and the augmented elements obstruct the vision of the user’s hands.

As a result of the compromised functionality and 3D image degradation using the hand occlusion feature on both Samsung S10e and iphone 11, the concept was amended. The application would instead be used as an educational tool where the procedure would be demonstrated using animation in augmented reality which could be viewed either by using this mounted on the table or mounted in a headset. The user would then perform the task either alongside of at the end of the animation. With screen recording active, it would be possible to record your own performance for later self-reflection, review of skill progression or gain feedback from a supervisor.

3.2.1 Scene development

The application aesthetic was aimed at being simple and easy to navigate. The opening scene is simple (fig 10.), this gives an option to proceed to a clinical scenario, aimed at improving decision making and the non-technical skills of putting the DAS guidelines into clinical context (fig 11). You can however skip this and proceed directly to the animation scene.

The animation scene has two options either it can be table-mounted, or it can be placed in a head mount (fig 12). The head mount is a low-cost apparatus, to allow for trainee accessibility; into which the phone can be placed with the screen projecting the view from the camera whilst mounted on the head. This was designed to offer a first-person view of the trainees performing the simulation whilst allowing hands to be free and uninterrupted. This would help in re-watching to aid in procedural recall, but also offers anonymity if external examination or scoring was to be used. To give a stereoscopic view, dual raw images with render textures placed on them were used, one for each lens. To counteract the curvature of the lens when looking at the 2D scene presented on the mobile screen, the images needed to have a convex or fisheye adjustment. Though there are multiple techniques to make this adjustment, the most common of which being shaders. However, with trial and error these were amended using an add-on post-processing package, using the lens distortion function (fig 13). A distortion degree of 45 felt to offer the best counter-curvature with the least edge distortion.

The table mounted view is shown here (fig 14-15) where it has the augmented reality head and animated hands that perform the procedure by the ATLS method i.e. using tracheal dilators and by the DAS guidelines i.e. using a bougie for insertion (fig 16). Each animated step has pop up descriptions of the process.

3.2.2 Additional features

Additional features included in the scene is a timer to allow for the trainee to keep track of their own procedural time to demonstrate progression or improvement. This can be activated by either pressing the ‘start’ UI button or saying “start” with voice activation. The voice activation function was developed as the buttons would be inaccessible when the phone is mounted in the headset, but also to allow smoother transition into task practice for the trainee in either mode. “Stop” “reset” and “exit” are therefore also recognised though this voice control function. This was created using a speech-to-text system that invokes an action based on the text recognised. This was created with speech to text asset ‘Mobile Speech Recognizer’ from the asset store. However the script was modified to allow the listener to automatically reset after each word produced rather than repeatedly pressing the listener button as intended. This had differing functionalities based on the operating system (IOS or Android) used.

3.2.3 The animation

The animation was created within Unity engine and lasted 1min30seconds. This was created as visual instructions, with informative panels appearing adjacent to the 3D head in sequence demonstrating the steps in performing the cricothyroidotomy. Each of the components of the animation were imported under one empty GameObject to which the animation was attached. This consisted of a Head and neck model and right and left hands, which were purchased from SketchFab, chosen for their low polygon count with highpoly detail baked on. This offered a greater deal of detail for the simulation than could be produced in the time allowed. Other components were a sterile drape, scalpel, local anaesthetic, bougie, tracheal dilators and endotracheal tube which were created using 3D studio max as low polygon objects.

The 3D hand models were purchased in the anatomic position; however, the procedure requires the left hand to perform the laryngeal handshake and the right hand would need to be able to hold and manipulate the surgical equipment to demonstrate the procedure. To do this the hands were first imported into 3DS max where the models were rigged. This was done by inserting bones similar to real metacarpals; however, the carpal bones were instead replaced with five bones attached to an anchor. These bones were then subject to a skinning modifier to the hand mesh. This allowed the hands to be posed and moved into the positions to grab the surgical instruments and stabilise the larynx to perform the procedure.

The animation demonstrates the steps in performing CCT whilst describing the action in pop up boxes. The animation begins as soon as the scene opens, and the target image is visualised. It continues through the steps until completion at which point all components disappear from the scene.

3.1.1 Model amendments

As the AR superimposed head and neck animation was not possible the model required alteration that allowed the trainee to adequately identify the landmarks and enact the procedure (fig 5). The aim of this was to create a cheap and easily reproducible surround that can simulate the surrounding anatomic structures. A surround was hence created using foam from packing material found freely in the theatre department (fig 6). This was carved into a neck shape and a funnel shape into which the model can be placed securely. The cricothyroid membrane was simulated by using a finger cut from a disposable glove, size large. This encircled the cricothyroid interval and created enough tension for the imitation of the cricothyroid membrane. A thyroid gland was carved from another small sponge, in the classic butterfly formation, however this was optional.

Finally, skin was created; this skin was produced using 1tsp powdered agar, 2 tbsp of vegetable glycerine and water each, with flesh coloured pigment added from generic foundation. This is boiled to activate and poured flat to set into a flat rubber-like material that can be laid atop the model. Setting takes approximately 10-15mins at room temperature and the sample can be re-heated and re-set multiple times. Hence this has created a fully re-useable and very cheap laryngeal model. Cost of 3D printing excluding labour hours was approximately £10, the foam was refuse and the skin costs 13p per section, leading to a CCT simulation for less than £15, that is reusable and free from animal tissue.

3.4 Pilot test

A pilot test was carried out to assess the application's usefulness and usability as well as the model's content and face validity.

3.4.1 Participants

There were four participants available to voluntarily rate the mobile application and model. The model separately was assessed during an airway training day for theatre staff in which nineteen participants were recruited.

3.4.2 Procedure

The testing was carried out in the theatre department of Raigmore Hospital. Each participant consented to partake in the study and were informed that they could withdraw at any time. Information sheets pertaining to both the procedural steps and the study concept were provided. The application was available on both an Apple iPad, iPhone and android to allow for user preference. The four participants using the application used both the table-mounted and head-mounted variations and performed the procedure afterwards. The nineteen model-only participants were shown pictorial representations of the procedure steps and verbally described (fig 5-6). Then each participant performed the procedure as per Plan D and plan E of the DAS guideline (fig 16). Once the participant had completed these tasks they were given a questionnaire to complete and were free to leave, the skin and cricothyroid membrane were then replaced for the next participant.

3.4.3 Data analysis

The questionnaire given to participants contained basic demographics such as job title, level and exposure to CCT previously. The statements regarding the application and model were rated on a 5 or 10-point Likert scale (1=strongly disagree,2 = disagree, 3=Neutral, 4= Agree, 5= Strongly Agree) there was a number of direct yes or no questions followed by open-ended questions at the end of the questionnaire pertaining to particular positives and negatives and another relating to areas for development.

4. Results

The following graphs (graph 1-4) depict the results of the questionnaire. Overall, participants' responses to both the application and the model were very encouraging.

4.1 demographics

Nineteen participants were recruited during an airway training day, all of these were part of the theatre team with anaesthetic doctors leading the majority (n=16). The participants ranged in career level from consultant (n=4) registrars (n=10) others were nurse practitioners and students. No participant had previously performed FONA on a real patient, thirteen had previous exposure through simulation, others either had no previous exposure or chose not to answer. When asked which step in the procedure was the most intimidating five found the decision to proceed to CCT the most daunting, five found making the incision and four found localising the cricothyroid membrane, i.e. identification of the anatomy, the most intimidating.

For those who assessed the application, (n=4) two were anaesthetic trainees, one a surgical registrar and one junior doctor without a specialisation. None had previously performed nor assisted a cricothyroidotomy being performed three had at least one previous exposure through simulation

4.2 Observational evaluation

Observing the participants using the application and the model during pilot user testing was immensely useful. From these observations and verbal comments made, the concept was very well received, AR had an added attraction as a novelty and the participants were keen to use both the application and practice on the model. Regardless of the initial level of enthusiasm each of the participants had great difficulty in using the application in the head mounted setting. One participant felt sick when wearing it, this improved, but hindered their experience of the application. In performing the procedure with the headset on, the participants struggled significantly as the lenses altered their depth perception as well as putting both the instruments and the target, cricothyroid membrane, in unexpected places. This was concerning when watching the participants with the scalpel, reassuringly they were able to coordinate their hands and navigate the instruments slowly however this clearly is not appropriate to practice skill fluency. There was significant improvement in the efficiency and co-ordination when observing the participants perform the procedure without the headset on, in the table mounted mode. The audio, i.e. background theatre noises, ECG monitor beep and stridulous noises that were created to enhance the theatre simulation and recreate the stress of the situation; was also felt to be unnecessary and detract from the applications usefulness.

when assessing the model many of the subjects were surprised at the true size of the female larynx. This made them appreciate the practice on a model as the unexpected small size may lead to difficulty in reality. Many were grateful, and appeared to enjoy the novelty, of the hands-on practice when they have had previous very little exposure to this procedure.

4.3 Open ended questions

When asked if there were any factors, either positive or negative, about this simulation many of the comments were positive. One participant stated that they “really liked that it is not animal tissue”, another found it “useful that it is reusable”. A student found “it useful to see the steps before performing them”, others commented on the ease at which it can be transported and the usefulness of the anatomic accuracy. Free text recommendations were also very helpful, one participant felt that “multiple models would be useful to demonstrate variable anatomy i.e. female, male and paediatric” another felt that a fixed head model would be useful for context. A couple of participants mentioned the use of this model in a full team simulation with non-technical skills and decision making, with simulation of the theatre sounds and surroundings.

5. Discussion and future work

Many simulations currently on the market have limitations such as cost, accessibility, poor anatomic realism, and ethical issues. Here we present a front of neck access simulation that is low cost, completely ethically sustainable, reproducible, and reusable. With the addition of a mobile application, the steps of the procedure can be easily demonstrated and can be used to record your own performance for later reflection and attaining feedback from supervisors.

Nevertheless, this research has further development potential. As technology improves and hand occlusion becomes possible or indeed formal AR headsets become cheap and mainstream, full mixed reality simulation in CCT can become a real possibility. Until this time it is clear that the technology is not yet at a functional stage where a mobile device can be mounted in simple headsets for the purposes of AR and surgical simulation. Based on the impaired depth perception and inability to see one's hands when performing a procedure with a scalpel safety is a main concern. However, there is still potential in this application in the table mounted setting as an educational and training tool. Firstly, the animations can be made in higher quality with faster processing times and smoother transitions. This can be adapted to have a scene with the animation and descriptive pop-ups as a training or educational scene; then have a separate scene that records the participant with side by side with the animation to make assessment of the steps. This will allow for mastery learning as the steps can be graded in efficacy of movement, mistakes, time to adequate ventilation and procedural accuracy; and can be repeated until each step is mastered. With increased technology this scoring may become automated using hand tracking scoring systems.

Further educational scenes within the application would be of great help to allow understanding of the surrounding structures and allow for recognition of variance. From the feedback a good proportion of the participants found the decision to proceed to CCT one of the most difficult steps. This is understandable, and many factors such as the surrounding team, clinician experience or indeed clinician hubris in intubation ability can be factors that can cause deviations from the DAS guidelines and can delay progressing to FONA and can increase morbidity and mortality. Although this application offers a clinical scenario that demonstrates a CICO scenario and deteriorating patient; more scenarios with differing complexity would be useful to help improve future decision making and make the trainees more comfortable making the leap to FONA.

In terms of model development, I feel that the feedback has been very positive to the concept of a reusable cheap model. Research has suggested that the low fidelity models are just as useful in skill acquisition, especially when assessing a task that can be repeated until automated at mastery level. Subjectively and based on comments from the participants, the anatomic accuracy is beneficial both in making the trainee aware of position of landmarks when palpating but also in the degree of resistance to expect when inserting the endotracheal tube. One limitation is the rigid resin material in which this protype has been printed in. Though this is cheap and therefore will be able to be reproduced easily and disseminated, the rigidity deters from the practical experience. Upon further research there are multiple other semi-rigid silicone based options that may be able to give the tensile strength and flexibility to imitate the larynx cartilaginous skeleton. This has supply issues but does not drastically alter the over all cost of the model.

One comment from a participant mentions the use in various sizes to represent the morphometric differences seen the larynx better gender and age. Hence creating interchangeable models that can be placed within the overall neck structure. This again can help trainees recognise the anatomical landmarks but also the resistance and angle of insertion between anatomically variable patients. Should this simulation be a success there is no end to the possibilities that mixed reality training simulations could have, such as surgical tracheostomy, central venous line insertion, fine needle aspiration or even thyroidectomy. These head and neck procedures could easily be performed on a similar model with relatively little modification to the mobile application.

Finally, this simulation highlights the need for a cricothyroidotomy trainer within a department. Zero participants had encountered a cricothyroidotomy in practice and only 68.4% had had access to simulated training. Based on the Likert questionnaire the majority of the department not only agree that a CCT trainer should be introduced into the department, but that this model is adequate for this purpose. The future goal will be to mass produce these models to offer to new trainees either as take-home training models or easily accessed in each department. The application could be disseminated to all trainees at each induction to the department. This could then be integrated into the current IST curriculum, with set scores and grading of each step to be reached to ensure uniform performance. Supervisors can monitor this and offer personalised or anonymised feedback as incentivisation. Once uniform performance has been reached it should then be monitored that the simulation is used at least once every 90 days to avoid skill decay (Higgins, Madan, and Patel 2020).

Conclusion

Here we present a mixed reality training model to perform cricothyroidotomy. It is cheap, easily reproducible and reusable to suggest that every department could have one and there is potential to disseminate to the surgical and anaesthetic trainees. Based on opinions of participants there is a need for this and a willingness to take part in this training. There are of course further development required to reach its full potential however it has the ability to not only allow repeated practice at the physical task of cricothyroidotomy, but to improve the knowledge of the steps, the clinical indication, the anatomy of the area and finally allow for self and supervisory feedback. This could lead to mastery leading and improved confidence in surgical and anaesthetic trainees and could be integrated into the current training curricula.

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