

Extending the application of virtual reality simulation in temporal bone anatomy and advanced surgical training.

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Abstract

Cochlear implant surgery has a strong foundation in the treatment of profound hearing loss. In the last decade, there have been marked developments in technology which have enabled the expansion of eligibility criteria. Cochlear implantation is now offered to patients with residual low-frequency hearing or those with unilateral or asymmetrical hearing loss. It is evidenced that to optimise hearing outcomes for patients with residual hearing, it is necessary to reduce the trauma during the insertion of the cochlear implant, in particular by precise surgical technique.

Current temporal bone surgery training, including cochlear implant surgery, is based on an apprenticeship model, where registrars observe and practice with consultant supervision. Prior to performing surgery on a patient, it is common practice to perform cadaveric temporal bone dissections. In addition to concern regarding decreasing availability of cadaveric temporal bones are financial constraints and regulations that reduce teaching time available in surgery. The generally low caseload, specifically relevant to cochlear implant surgery, minimises the opportunities for apprenticeship training. As such, this traditional model of training is not maintainable.

Similar pressures face the training of anatomy of the temporal bone to medical students and junior doctors. While otologic presentations make a sizable proportion of presentations to emergency departments and general practice, due to the reduction in medical school training time, education in otology is in decline.

Virtual reality (VR) surgical training is an attractive adjunct to the current training pathway as it provides a cost effective platform where risk-free, repetitive practice is readily available. VR also has several unique benefits. By presenting automated feedback, VR training allows for self-directed learning. In addition, automated assessment tools have been validated to objectively measure performance. While the effectiveness of VR simulation for mastoidectomy training has previously been well established, to the author's knowledge there have been no VR simulators adapted to teach more complex temporal bone surgery such as cochlear implant surgery, or clinically oriented temporal bone anatomy.

The aims of this thesis were: 1) to determine the viability of expanding the role of VR simulation in otology, including anatomy education and advanced temporal bone surgery and 2) to explore patient factors that relate to surgical technique in cochlear implant surgery. To these ends, several investigations were performed.

Firstly, a randomised control trial was conducted to determine whether a clinically oriented VR temporal bone simulator module improved anatomy knowledge of medical students and junior doctors. Participants were randomly allocated to three groups of differing display modality: stereoscopic 3D, monoscopic 3D and 2D presentations. The participants completed a pre-tutorial questionnaire before working through the self-guided tutorial. The module was followed by a post-tutorial questionnaire and a retention questionnaire at 6 weeks. The questionnaires assessed factual anatomic knowledge, spatial relationships and clinically oriented knowledge as well as student's perception of the display modality. It was observed that the module was effective in imparting factual knowledge in all modalities. The students exposed to the 3D technologies performed better in the spatial relationship and clinically oriented questions. The Stereoscopic 3D modality showed particular benefit for ease of use.

Secondly, a training module specifically designed for the surgical approach to cochlear implant surgery was assessed with a prospective pre- and post-study of ENT registrars. All participants were exposed to the same training module that included concurrent and terminal feedback on temporal bones with a range of common anatomical variations. The participants' performances were compared before and after the training. The assessment temporal bones used at the end of training consisted of a mirror image of the one used prior to training and one novel temporal bone. It was found that there was a significant improvement with a large effect size after training for both the previously encountered temporal bone and the novel temporal bone.

Thirdly, a conceptual anatomical study was performed using the University of Melbourne temporal bone simulator data. The study explored patient factors that affect the surgical technique used in approaching cochlear implantation. In particular, the relationship of surgical preparation of the facial recess to the acceptable electrode trajectories into the cochlea. It was found that acceptable trajectories through a round window membrane approach most likely originated superiorly in the facial recess, adjacent to the facial nerve. Conversely, acceptable trajectories through a cochleostomy approach most likely originated inferiorly in the facial recess, adjacent to the junction of the facial nerve and chorda tympani. Furthermore, the skeletonisation of the facial recess was found to be critical in the preparation of the temporal bone for a cochleostomy approach.

The results presented throughout the thesis will help guide medical educators in the areas of otology and cochlear implant surgery. These results suggest the viability of an expanded application of virtual reality temporal bone simulations to use in anatomy education and advanced temporal bone surgery training.

Declaration

This is to certify that

1. The thesis comprises only my original work toward the PhD except where indicated in the preface.
2. Due acknowledgement has been made in the text to all other material used.
3. The thesis is fewer than 100,000 words in length, exclusive of tables, bibliographies and appendices.

Bridget Copson

January 2020

Preface

This thesis is a collaboration of the results of a series of projects undertaken in the 4 years from 2015 to 2019 by the author with the support of the University of Melbourne's virtual reality surgical simulation group. This group is based at the Department of Surgery (Otolaryngology), Royal Victorian Eye and Ear Hospital. The following collaborations are forthwith acknowledged:

Project 1: Development of a virtual reality clinically oriented temporal bone anatomy module with randomized control study of presented three-dimensional display technology

Bridget Copson designed, analysed, interpreted the data, drafted and revised the manuscript

Laurence Sorace participated in student recruitment and revised the manuscript

Sudanthi Wijewickrema developed the VR module and revised the manuscript

Randall Jones participated in experimental design and revised the manuscript

Stephen O'Leary made significant contributions to the design of the study and manuscript

Project 2: Supporting skill acquisition in cochlear implant surgery through virtual reality simulation

Bridget Copson wrote the first draft of the protocol, designed, collected, analysed and interpreted the data, drafted and revised the manuscript.

Sudanthi Wijewickrema designed and created the VR modules, revised the manuscript.

Yun Zhou designed and created the VR modules

Patorn Piromchai assessed the videos and revised the manuscript

Gregor Kennedy revised the manuscript

James Bailey revised the manuscript

Robert Briggs designed and recorded the audio for the modules

Stephen O'Leary made substantial contributions to the design of the study and the manuscript

Project 3: Surgical approach to the facial recess influences the acceptable trajectory of cochlear implantation electrodes

Bridget Copson designed, analysed, interpreted the data, drafted and revised the manuscript

Sudanthi Wijewickrema developed the software, analysed the data and revised the manuscript

Xingjun Ma developed the software

Yun Zhou developed the software

Stephen O’Leary and Jean-Marc Gerard made substantial contributions to the design of the study and the manuscript

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Chapter 1: Introduction

Anatomy and surgical training have suffered a paralleled increase in number of trainees, decline in teaching time and reduced access to cadavers for dissection (1-5). These pressures have prompted the integration of alternative educational tools such as three dimensional models and simulations (6-9). The field of otology has several unique pressures in training. Firstly, temporal bone anatomy is complex and the critical structures have a close relationship in a compact area (10, 11). As a result, developing high fidelity alternative temporal bone models can be challenging. Secondly, although otologic conditions are commonly seen by general practitioners and emergency physicians (12, 13), otology anatomy is underrepresented in medical curricula (14-16). Thirdly, as a result of the expansion of clinical eligibility for cochlear implantation, there have been predictions of an increased need for surgeons trained in advanced temporal bone procedures (17). This expansion of clinical criteria is related to the use of cochlear implants in patients who have residual low frequency hearing (18-20).

Addressing these challenges is imperative to safe medical practice in otology and is applicable to medical students, junior doctors, trainees and surgeons alike. The reduction in time and resources allocated to anatomy education risks an inadequate level of anatomy knowledge to practice safely (21-23). Anatomic error is an important cause of avoidable patient morbidity and mortality (24). In otology, surgical trainees have a reduced exposure of clinical experience to gain sufficient operative competency (25). Complications of surgical procedures performed by trainees have been previously attributed to the necessary 'learning curve' as a result of trainees practicing their technique on patients (26). Furthermore, in cochlear implant surgery, surgical technique has been established as a critical component in the prevention of residual hearing loss (27, 28).

To maximise the learning outcomes, anatomy educators have proposed systems-based curricula and the integration of multiple learning resources including virtual reality simulation (29). Simulation has also been proposed as imperative in surgical training to protect patients from undue risk associated with the inevitable learning curve (30). Furthermore, simulation based courses have proven their potential in continuing medical education (CME) for established surgeons (31, 32).

In the field of otology education, virtual reality (VR) temporal bone simulators are a promising adjuncts in training temporal bone dissection (7). VR temporal bone simulators have been found to adequately replicate the educational experience of cadaveric temporal bones (33). As an educational adjunct, compared to physical models and cadaveric temporal bones, VR simulators have the added benefits of infinite repetition, ability to "undo" mistakes and automatic recording of performance metrics (11, 34, 35). Furthermore, the performance metrics recorded by VR temporal bone simulators have been validated for objective, automated feedback and assessment in mastoidectomy training (34, 36-40).

Although VR temporal bone simulators have demonstrated benefit to surgical trainees in the procedure of mastoidectomy (for example, improved cadaveric dissection performance (35, 41) and retention of skills (42)), further application of these VR temporal bone simulators beyond mastoidectomy training has not been explored.

Motivations for the research

The motivation for this thesis was to identify and alleviate pressures in training temporal bone anatomy education and advanced temporal bone surgery, including specific surgical techniques as related to cochlear implant surgery. To this end, we developed and validated VR simulation modules with the objective of using these as adjuncts to traditional temporal bone anatomy and surgical training.

Several solutions have been identified in the literature to foster effective anatomy education (43). While dissection remains an integral part of anatomy education (44, 45), dissection can be offered to students via a virtual simulator (43). Additionally, developing curricula of anatomy with a clinically orientated approach is engaging to students (46) and has proved an effective approach (47-49). Preliminary studies have shown promise for VR temporal bone simulators in anatomy education (50, 51), yet these modules do not integrate any correlating clinical relevant information. To bridge this gap, we propose a combined approach to temporal bone anatomy education by devising and validating a clinically oriented VR temporal bone anatomy simulator module.

Furthermore, expanding on the previous successes of VR temporal bone surgical simulators in mastoidectomy training (35), we propose a VR temporal bone simulator module for the training of cochlear implant surgery. We validated this module using an assessment tool developed for cochlear implant competency (52).

Surgical techniques used for cochlear implantation are now being re-evaluated for the purpose of maintaining residual hearing (27, 28). In order for VR temporal bone simulator modules to remain current to this advancing literature, these surgical techniques should be integrated into the simulator where possible. Additionally, the anatomic data of the segmented cadaveric temporal bones used in VR temporal bone simulators provides a platform for the investigation of variation of anatomic relationships (53). Finally, in chapter 4, we used the VR temporal bone simulator platform to explore the impact of particular surgical techniques on acceptable cochlear implant electrode insertion technique.

Organisation of the thesis

This thesis includes a collaboration of content from a range of disciplines. The themes include technologies and advancements in VR simulators in surgery and anatomy education and surgical technique in hearing preservation in cochlear implantation. As such, in Chapter 1, the literature review is presented in two main sections. It begins by outlining the pertinent aspects of cochlear implant surgery techniques. The techniques discussed have an emphasis on reducing trauma for the current practice of hearing preservation cochlear implantation. These techniques are fundamental to the development of a VR advanced temporal bone surgery model. The second part of this literature review explores virtual reality simulation in temporal bone anatomy and surgical education. The validation of the current temporal bone VR simulators is detailed. The current advancements in VR simulation are discussed. This is followed by a discussion of the current advancements in simulation anatomy education.

Figure 1 illustrates the approach used to combine content between these disciplines in order to arrive at the aims of this thesis. **Chapter 2** outlines the development and assessment of a clinically oriented temporal bone anatomy VR simulator module. **Chapter 3** discusses the development and assessment of an advanced temporal bone procedural VR simulator module. **Chapter 4** explores the modelling of acceptable virtual electrode trajectories into the cochlea and how surgical approach,

anatomy and electrode dimension impact these trajectories. **Chapter 5** provides a summary of the results and a general discussion including implications of the findings and future directions for research.

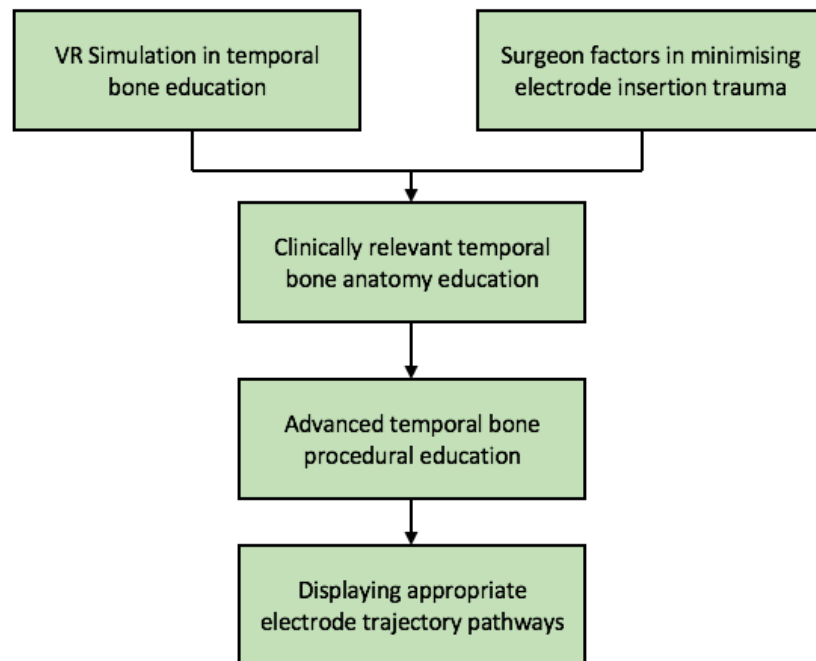


Figure 1.1: Flowchart of the approach to the thematic content explored in this thesis.

Literature review

Electroacoustic simulation and preservation of residual hearing

The cochlear implant in its multichannel form was initially offered to patients with profound bilateral deafness from the late 1970s (54-56). Over the following decades, marked advancements in technology of the electrodes and implants allowed for criteria to widen and include patients with residual low frequency hearing (18-20). Further advancements in hearing augmentation combines cochlear implantation and a hearing aid in the same ear. This is termed Electro-acoustic simulation (EAS). The indication of EAS includes patients with profound high-frequency hearing loss but intact low frequency hearing (57, 58).

Electroacoustic simulation is of particular benefit in improving speech perception in the presence of background noise (59-61). This benefit can translate to significant real-life outcomes such as higher income and improve quality of life (62, 63). Unfortunately, after insertion of the cochlear implant, recipients can lose some or all of their residual hearing (59). This hearing loss can occur immediately after surgery (64), or can be delayed by up to several months (65). Surgical technique forms an important aetiology of post implantation hearing loss (27, 28), the components of which will be discussed forthwith.

Surgical technique and post-implantation loss of residual hearing

Intracochlear dislodgement

Positioning the electrode in the scala tympani (ST) results in better speech perception outcomes and improved preservation of residual hearing as compared to scala vestibuli (SV) electrode placement (28, 59-61, 66-71). The rationale for improved hearing is the proximity of the electrode to the spiral ganglion cells and dendrites (72) and also protection from trauma of the scala media by the basilar membrane and osseous spiral lamina (73). Despite the aim of a scala tympani placement, dislodgement to the scala vestibuli occurs in a variable proportion of cochlear implants (66). This dislodgement is caused by high grade trauma to the basilar membrane or spiral ligament (74). This degree of trauma is visible on high resolution computed tomography (CT) imaging. Dislodgement into the scala vestibuli, as determined through CT imaging, has been correlated to poorer function outcomes of recipients (28, 75, 76). The inferior outcomes seen in scala vestibuli dislodgement are due to a combination of the aforementioned trauma of insertion and also the suboptimal resting electrode position within the cochlea (66). Surgical approach to the cochlea impacts the likelihood of electrode dislodgement (28, 75, 77); a cochleostomy approach is more likely to result in dislodgement of electrodes. However, these findings may be due to the variable positioning of a cochleostomy (see Variability in surgical practice of cochleostomy) (78-80).

Rationale for the need for both cochleostomy and round window membrane approaches

The round window membrane approach is the traditional electrode insertion approach (81). However, when straight multichannel electrodes were introduced, there was a transition to extending the insertion to an antero-inferior cochleostomy for an improved view and insertion angle into the basal turn of the cochlea (81). The benefits and disadvantages of both cochleostomy and round window membrane approach have been assessed thoroughly (28, 66, 72, 79, 82, 83). Pau et al. recorded sound

pressure levels in excess of 130dB with drilling cochleostomies on four cadaveric temporal bones (84). Despite the small experimental number, the authors suggested consideration of round window membrane insertion to minimise acoustic trauma (84). Other benefits of round window insertion are the smaller risk of bone dust placement in the scala tympani, minimal loss of perilymph (82) and reduced incidence of post-operative vertigo (83). Conversely, there is concern with a round window insertion that the initial trajectory of the electrode is directed at the modiolus and hence resistance is encountered and insertion depth is limited (85). In addition, the variability in the angle of the hook region of the basal turn can influence the availability of an insertion vector through the round window membrane (86).

Two studies which examined the effect of location of insertion on clinical outcomes showed similar post-operative speech perception up to 12 - 14 months after either round window membrane insertion or cochleostomy (87, 88). These studies used different protocols to specify which approach was used. Adunka et al. used a round window membrane approach when the RWM was facing posteriorly but a cochleostomy when the RWM was facing inferiorly (87). Kang et al. suggested RWM insertion when the RWM was visualised completely but a cochleostomy after drilling of the bony overhang when RWM visualisation was suboptimal (88). These studies suggest that the anatomic variation of the cochlea is such that there is a role for both cochleostomy and round window membrane approaches.

This idea has been reiterated in the most recent meta-analysis of hearing preservation methods in cochlear implantation authored by Snels et al. which synthesised the results of 26 papers (936 patients) (89). With regards to cochleostomy and round window membrane insertion, the round window membrane approach was superior in hearing preservation outcomes only at a 6 month follow up, but not at a 12 month follow up. However, this meta-analysis did not explore the differences in the study protocols that specified the conditions for the use of round window or cochleostomy. The results of this metanalysis combined with two previous metanalyses (27, 90) suggest that both the cochleostomy and round window approaches may be appropriate depending on anatomic circumstance.

Adequate exposure of the round window

Regardless of the intended approach to electrode insertion, adequate exposure of the round window membrane is pertinent in minimising electrode insertion trauma. Roland et al. observed an increase in round window membrane visibility of 1.5 to 3 times after drilling of the niche overhangs (82). This was confirmed by Shapira et al. who noted a threefold increase in area of the round window visualised after drilling of overhangs (91). Briggs et al. similarly concluded that to perform a safe and effective cochleostomy, sufficient access is required through the facial recess to visualise the entire round window niche and membrane, and in certain cases the crista fenestra may need to be removed (79).

Variability in surgical practice of cochleostomy

Complicating the aforementioned approach to cochlear electrode insertion and hearing preservation is the variability in surgeon's daily practice. A survey performed by Adunka et al. assessing preferential surgical approach to cochlear implantation highlights the marked variation in approach to cochleostomy (78). Of the 55 surgeons surveyed, 16.4% - 23.6% described the preferential approach of a superior cochleostomy. In addition, of the 55 surveyed surgeons, 84% used cochleostomy approaches exclusively when inserting cochlea implant electrodes, yet only 50.9% of all respondents drilled the round window bony overhang.

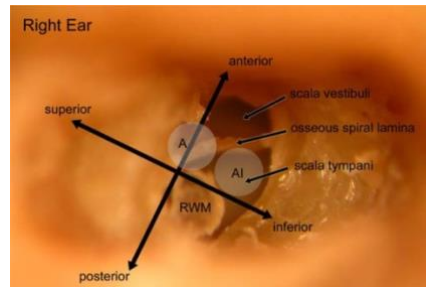


Figure 1.2: Photograph of a right temporal bone with the basal turn of the cochlea removed identifying the position of anterior (A) and anteroinferior (AI) cochleostomies and their relationship to intracochlear structures (from Friedland et al 2009).

The survey did not investigate the reasons for these variations in surgical approach. However, these results suggest that improving understanding of surgical anatomy, in particular, anatomy of the promontory and relations of the round window and cochlea should be considered in methods of minimising insertion trauma during cochlea implantation. Indeed, in a follow up study 6 years later, there had been significant increase in the respondents choosing an inferior or anteroinferior cochleostomy (92). However, there were still 8-10% of surgeons who performed a superior cochleostomy placement. In the same survey, it was identified that only 66% of respondents identified the facial nerve on exposure of the facial recess and 69.2% the chorda tympani. While there has been an improvement in surgical practice for an atraumatic electrode insertion technique, these findings suggest that further education in this area is required. The authors called for further research into the benefits of skeletonising the facial recess in providing safe cochleostomy placement.

Insertion vectors and trajectories

Once the insertion point to the basal turn has been prepared (whether through cochleostomy or round window membrane), the surgeon must insert the electrode via the facial recess and into the basal turn of the cochlea. Meshik et al. described an optimal insertion vector to avoid insertion trauma (93). The proposed insertion vector is coaxial to the centreline of the scala tympani. Insertion vectors that remain linear to this centreline axis have the potential to limit trauma to the spiral ligament and basilar membrane (91, 94-96). However, depending on the orientation of the cochlea, the vectors modelled by Meshik et al. have a close relationship with the facial nerve and may transect it (93). The practicality of inserting an electrode in this optimal insertion vector is further complicated by the lack of intra-operative visual cues or anatomic landmarks to guide the surgeon (97). The orientation of the RWM may reflect the rotation of the cochlea (72). While some researchers have used the RWM orientation to guide decision making for insertion approaches (cochleostomy or RWM) (87, 88), there remains no systematic approach to using the RWM orientation to guide insertion vectors. Experienced surgeons instead rely on an excellent mental representation of cochlea anatomy to perform a cochlear electrode insertion that is linear to the optimal insertion vector (97) (80).

Approach to preparing the facial recess

The aforementioned close relationship of a cochlear implant electrode trajectory with the mastoid segment of the facial nerve suggests that the facial nerve requires thorough skeletonisation in order to allow for safe straight line insertion trajectories (93). This practice has been described by experts in the field as an important technique to visualise the anatomy of the round window membrane and promontory (79, 98, 99). Skeletonising the facial nerve increases the likelihood of visualisation of the round window membrane through the facial recess (100) which is necessary for a safe electrode insertion (79). However, despite thorough skeletonisation of the facial nerve, given the variability of cochlea anatomy, the round window membrane may not be visualised in all cases (101, 102). Thorough skeletonisation of the facial nerve risks neural sheath injury (103) and in the worst-case scenario, can cause facial nerve paralysis (104-106). While it has been suggested that the risk of facial nerve injury should not preclude a surgeon from skeletonising the facial recess (107), Briggs et al. have raised concerns that for this reason, surgeons are not confident completing the facial recess skeletonisation (79).

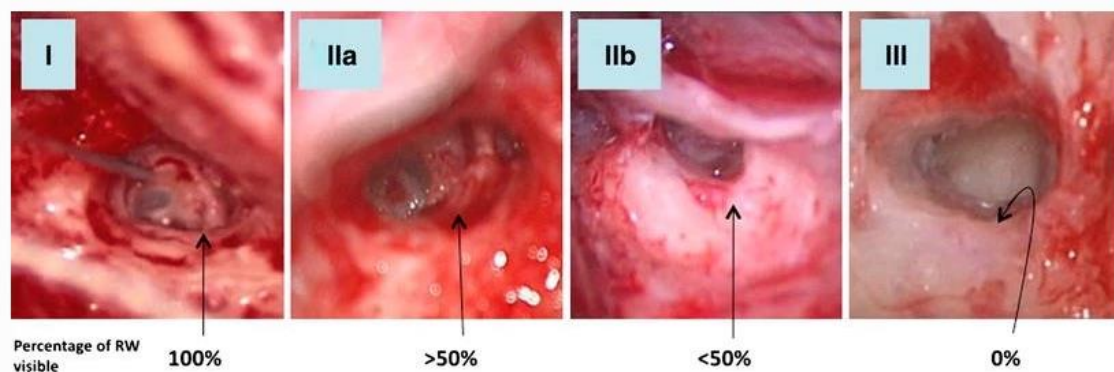


Figure 1.3: St Thomas' Hospital classification of visibility of the round window membrane from a posterior tympanotomy approach. Type I the full round window membrane is accessible, Type IIa >50% of the RWM is accessible, Type IIb <50% and Type III none of the round window membrane is visible (from Leong et al 2012).

Evolution of Electrodes and insertion tools

Concurrent with the progress in surgical technique has been the development of electrodes which maximise the potential for electrical hearing while minimising trauma during insertion (108). In general terms, the variables assigned to electrode arrays are: "straight or contoured, stiff or flexible and long or short" (109). Friedland et al. argue that because of multiple variables in each electrode arrays used in anatomical studies, direct comparison is difficult and suggests clinical data is more convincing when discussing electrode characteristics and hearing preservation (109). Another confounding factor is that although short electrodes allowing shallow insertion may be associated with improved outcomes, subsequent use of these arrays as electrical simulation alone may be limited (67). Thus, it may be clinically appropriate in some cases to accept an inferior hearing preservation outcome seen in electrodes affording greater insertion depths (110).

Contoured electrodes were designed to sit in a perimodiolar position, closely relating to the spiral ganglion cells. Doshi et al. found similar speech discrimination outcomes for post-lingually profoundly deaf patients after insertion of either a flexible straight or contoured electrode (111). Although the

electrodes were otherwise electrically identical, the location of insertion to the basal turn was different between groups with the flexible straight electrode more commonly placed via a round window approach and the contour electrode mainly inserted via a cochleostomy. Despite this limitation, it may be inferred that both straight and contoured electrodes are effective in providing beneficial speech discrimination outcomes when inserted appropriately. Furthermore, a study by Mady et al. suggests that the trauma inflicted at the time of electrode insertion may influence long-term hearing preservation outcomes (112). In their study of 45 cochlear implant recipients, those receiving the perimodiolar electrode had inferior short-term hearing preservation, yet an equivalent long-term hearing preservation when compared to lateral wall electrodes.

In addition to electrode design, style of insertion of the electrode has been evaluated with improved clinical outcomes seen using an “Advance off Stylet” technique for a perimodiolar placement of an electrode (66). This technique relies on the correct initial placement of the electrode tip to avoid tip fold-over or damage to the spiral ligament (108). As a result of a multi-centre, expert-led collaboration, a novel electrode design has been assessed (113). The Modiolar Research Array is a very thin perimodiolar electrode that is inserted with a removable straight sheath. The straight sheath limits the introducer insertion depth, preventing trauma of the lateral wall and the thin internal array allows for both cochleostomy and round window membrane insertions (114). Early clinical reports indicate this electrode can preserve residual hearing in the short and long term (115-117). However, tip roll over has been found to complicate the insertion of this electrode. While the mechanism is not well understood (118), surgical technique has been hypothesised to contribute to tip rollover. Despite the advancement in electrode design, these findings reiterate the importance of the aforementioned foundations of surgical technique as related to cochlear implantation.

Simulation in temporal bone procedural training

As previously discussed, surgical technique remains at the foundation of hearing preservation techniques in cochlear implantation. It remains pertinent to ensure upcoming surgeons have an excellent understanding of the procedure and underlying anatomy. In this regard, it is imperative to consider the methodology of training of temporal bone procedures, including training of relevant anatomy and procedural training. In the following review, the use of virtual reality as an adjunct to temporal bone anatomy and surgical training will be explored.

Current training in Otolaryngology

Surgical training in Australia has followed the worldwide trend to reduce working hours for doctors and the need to balance effective training with reasonable working hours has been acknowledged by The Royal Australasian College of Surgeons (RACS) (1, 2). There has been some concern that a reduction in working hours may negatively impact surgical training (119). Although the effect of these changes on surgical experience and patient outcomes remains undetermined, it is clear that there is a need for effective and efficient surgical education to minimise the impact of a reduction in work hours on surgical training (1). Current training in otolaryngology in general, and cochlear implant surgery in particular, is largely dependent on the combination of the apprenticeship model in the operating theatre and technical skills gained through cadaveric temporal bone laboratories (120-122). In the training for cochlear implant surgery, experts in the field are subspecialists and cases appropriate for educational purposes can be limited (52). In addition, increasing financial pressure risks a reduction in time available for teaching and a reduced faculty of teaching (123). Concurrently, with the expansion of surgical eligibility criteria for cochlear implants (18-20), there will likely be an

increase in demand for trained surgeons. Adding further pressure to the traditional model of training is the decreasing availability of cadaveric temporal bones (124).

Training in anatomy

Anatomy education in medical schools has suffered similar pressures to those in otolaryngology training; there has been a reduction in training hours and decreasing availability of cadavers for dissection (3-5). These changes have resulted in a reliance on didactic methods of teaching (43). As a result, medical students have been shown to have declined in the knowledge of anatomy (125-127). There are concerns that the anatomy knowledge of medical students is unsafe (21, 22). The impact of these changes is particularly worrying for students who intend to work a procedural field (128). In a survey of 204 newly graduated doctors regarding sufficiency of anatomy training in medical school, Fitzgerald et al. found that doctors who intended on training in surgery were more likely to feel that the anatomy training had been insufficient (3). To mitigate these issues, anatomy education has trended toward a systems-based approach, where anatomy education is integrated with basic and clinical sciences (48). While this integration approach has been implemented successfully in many medical schools (49), it has limitations in training advanced anatomic concepts and anatomic relationships (129). After collating the experience of the surveyed junior doctors, Fitzgerald et al. proposed a “vertical” integration of anatomy training, where topics are revisited in greater depth throughout medical school. They envisioned that there may be a role for anatomy departments and specialty schools, or commercial enterprises to deliver this ongoing “vertical” anatomy education. This mirrors the findings of the survey of 218 New Zealand medical students by Hammer et al, where 87% of respondents were in favour of revisiting anatomy topics during surgical clinical placements (22).

Adjuncts to training temporal bone anatomy and surgery

The aforementioned limitations in traditional temporal bone anatomy and surgical training have prompted evaluation of alternative adjuncts to cadaveric dissection. The main alternatives explored have been porcine dissection, three dimensional (3D) physical models and virtual reality temporal bone simulators (7, 130). Porcine dissection is not a commonly used alternative. Although the porcine middle ear anatomy is similar to that of a human temporal bone, the mastoid is not pneumatized and there lacks critical anatomic landmarks used for surgery (131). The “Pettigrew” temporal bone is a commonly used synthetic 3D model consisting of a plastic model casted from a cadaver temporal bone (10). While this bone has acceptable face and content validity for global otology skills and mastoidectomy training, it lacks critical structures needed for more advanced training (10). Further advancements in physical models have included the use of medical imaging data in printed anatomic models (8, 9, 132). These 3D printed bones have been found to have likeness in drilling qualities to human temporal bones and perceived value in surgical training (133). In addition, these 3D models have sufficient detail to perform advanced temporal bone procedures such as cochleostomy (133), middle ear prosthesis insertions (134) and cochlear implantation (135). However, these detailed, accurate 3D models are limited by cost (136). This is due to the need for multiple materials and a commercial printer, which can cost 400USD per model (133). Mowry et al. developed a realistic temporal bone model that could be made on a personal office 3D printer for the inexpensive cost of 1.92USD per model (136). However, the drawback with this model is the loss of sufficient detail in the middle ear for advanced temporal bone procedure rehearsal (137). Other drawbacks include its malodour, excessive dust formation, as well as time to produce (3.5 hours per

bone) (136). Furthermore, while these physical models have high fidelity, they provide no additional benefit beyond cadaveric temporal bones in terms of feedback or self-directed learning and are not suitable to use in developing standardised proficiency based curriculum (123).

Virtual reality simulation in surgical education

Virtual reality simulators are considered high fidelity simulators in their ability to demonstrate more complex tasks in a realistic style (138). The multiple benefits of virtual reality simulators in surgical education have been well demonstrated (139, 140). VR simulators provide a safe and ethical platform to trainees for repeatable, self-directed practice with real-time feedback (141-143). However, VR simulation has been slow to appear in surgical curricula (144-146). Barriers to implementation into surgical curricula have been identified, including transferability of skills, clearly defining goals and standardised and validated assessment tools (142, 147-149). These issues, among others will be discussed in the following sections.

Virtual reality simulation in otology

Virtual reality simulation is an attractive adjunct in otology surgery training as it provides a risk-free, learning environment which enables repetitive practice (150). VR simulation currently has a solid evidence base in mastoidectomy surgery. It has been shown to provide a similar educational experience to cadaveric temporal bone dissection (151). When used as a learning aid prior to cadaveric temporal bone dissection, it improves dissection performance (152). While these benefits may also be seen with a 3D printed temporal bone, VR has the added advantage of providing objective assessment of technical skills (153). In addition, it encourages self-directed practice, leading to improved learning curves (154, 155). The ability to provide real time feedback improves technical skills (156) and this as well as repeat performances improves retention of skills (152, 157). As a result of these findings, VR simulators have been integrated in to surgical training in otology for the procedure of mastoidectomy (158, 159). While VR simulation has been established as a training tool in foundation temporal bone surgery, there have been no studies to date assessing the use of this technology for advanced temporal bone procedures. Additionally, while these VR simulations are anatomically accurate, there is limited literature for their use in anatomy education (50, 51). Furthermore, neither of these two, low powered cohort studies present the temporal bone anatomy in a clinically orientated, systems-based approach.

Validation of virtual reality simulators in surgery

Current surgical training is based on the constructivist theory of "experiential learning" where learning is developed in a cycle from concrete experience, reflective observation, abstract conceptualisation and active experimentation (160). This learning cycle is pertinent to virtual reality simulators as it highlights that a simulator task should be followed by assessment and feedback (161). It also highlights the importance of validity, which suggests that a simulator resembles the procedure it is training reliably and is able to evaluate performance using objective measures (161-163). Validity can be further divided into face, content, construct and predictive validity (161-163). Face validity is a subjective measure of the realistic environment of the test and is commonly assessed using a questionnaire (25, 161-163). Content validity assesses the effectiveness of a simulator in providing the necessary skills needed in performing the procedure and is also usually a subjective assessment (25, 162, 163). Construct validity encompasses the ability of a simulator to differentiate the level of

expertise of the participant (for example novice or expert) and is closely related to predictive validity which compares a simulator's assessment to outcomes on alternate forms of assessment (25, 161, 162).

Current VR simulators in temporal bone surgery

The current available temporal bone simulators include the University of Melbourne Virtual Reality Temporal Bone Surgical Simulator (University of Melbourne, Australia), VOXEL-Man Temposurg (University Medical Centre Hamburg-Eppendorf, Germany), Ohio State University simulator (Ohio, US), and the Stanford surgical simulator (California, USA). All available temporal bone simulators use a PHANTOM haptic device to provide tactile/force feedback and virtual models are generated from computed tomography (CT) images of cadaveric temporal bones. A description of each of the simulators with a review of current available literature on validation is included below.

University of Melbourne Virtual Reality Temporal Bone Surgery Simulator

The University of Melbourne virtual reality temporal bone surgery simulator has been developed at the University of Melbourne, Australia in collaboration with The Commonwealth Scientific and Industrial Research Organisation (CSIRO) (164). The simulator set-up includes a three-dimensional (3D) virtually represented human temporal bone seen through 3D glasses. A haptically rendered pointing device is used to simulate the drilling tool. The virtual drill has burr sizes ranging from 1-9mm and has an optional "cutting" or "polishing" bit attachment. The simulator also includes auditory feedback. An initial cohort study in 2008 assessed the content and face validity by training 11 naïve surgical trainees on the VR simulator prior to assessing performance using a cadaveric temporal bone (164). Construct validity was confirmed in a study of 27 participants of varying surgical experience who were asked to perform a modified radical mastoidectomy on the VR simulator (153). Computer-generated metrics were used to assess surgical skill level and when multiple metrics were analysed concurrently, the simulator was able to predict the correct level of experience in 90% of cases. A further randomised control trial found improved performance on cadaveric temporal bone dissections after using a self-directed simulation module (165). Subsequently, construct validity has been confirmed using an objective assessment tool for competency assessment in cochlear implant surgery (52).

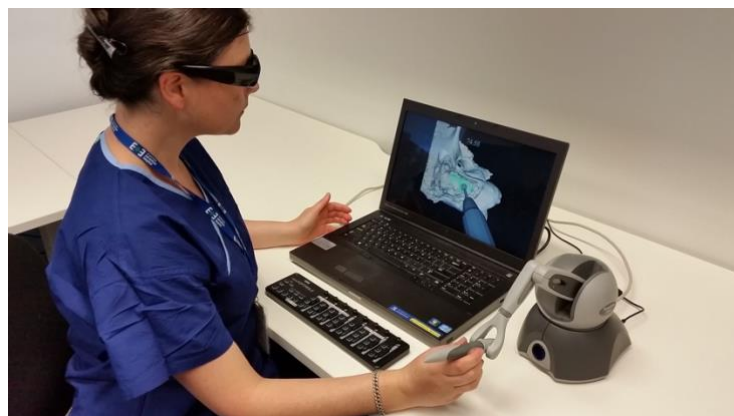


Figure 1.4: University of Melbourne Temporal Bone Virtual Reality Surgical Simulator.

Voxel-man Temposurg

The VOXEL-MAN TempoSurg simulator displays the volume rendered CT data in a stereoscopic manner. The angle and magnification of the display is adjustable, as is the size and rotation speed of the drill (166). Multiple studies have been performed to assess face and content validity of this simulator (120, 155, 167). Firstly, using a questionnaire addressing the ten features of effective high-fidelity medical simulation as identified by Issenberg et al. (168), the VT training was compared to traditional cadaveric temporal bone teaching (166). The VT was found to be more effective in allowing repetitive practice, control of difficulty and capturing clinical variation but performed inferior to cadaveric temporal bones for face validity and feedback. Face validity was further assessed in a study of 85 participants (120); although 70% of participants felt the anatomical appearance was acceptable, overall mean scores of face validity were below the acceptable range. Content validity was assessed in the same study and two further studies (120, 155, 167). Arora et al. found that content validity was rated favourably on a Likert-type scale (120) and Francis et al. found that 12 residents improved their technical skills in cortical mastoidectomy surgery as rated on an objective structured assessment of technical skills (OSATS) tool (167). Findings were similar in a study of 4 medical students (155).

Construct validation has also been confirmed in two studies. Firstly using expert assessment of recorded performance (169), and also where the metrics recorded by the Voxel-Man Temposurg simulator were analysed and were able to differentiate between levels of experience (170).

Stanford temporal bone simulator

The Stanford surgical simulator is comprised of two SenAble Phantom haptic devices used on a dual CPU PC to simulate drilling and suction (171). Construct validity was confirmed for a cortical mastoidectomy in a study of 15 participants of differing experience (4 surgeons, 4 registrars and 7 novices)(172). Performance was measured using internal device metrics as well as expert assessment. The participants were given an initial instructional video describing the procedure, as well as still images of expected stages of the procedure during the simulation session. The mean global scores given by the two expert assessors were significantly different for the novices compared to the participants with surgical experience ($p < 0.0001$). Additionally, an automated algorithm was used to compare various combinations of internally generated metrics between the participant groups; these included force, drill position, suction position and distance from the facial nerve. Using this method, these metrics successfully discriminated level of experience and most of the metrics were found to be consistent with the expert assessor global scores. While face validity was not assessed in this study, this simulator has been redesigned as a patient-specific temporal bone simulator (173). Computed tomography (CT) data of 30 patients were integrated into the VR simulation environment. Key images of the simulation were found to appropriately replicate patient specific intraoperative images and this suggests face validity of this simulator. However, the authors noted that the fidelity was not sufficient for surgical rehearsal and further development of this patient specific simulator is limited by sufficient technology in automatic segmentation.

Ohio temporal bone dissection simulator

The most recently published version of the Ohio temporal bone simulator (OSU) includes a binocular display device combined with a 3D Omni joystick to make selections and perform drilling. There is a “tutor” subsystem which is accessed through a menu selection and displays selected structures in the dataset (174). In a randomised control study of 80 participants, content validity was established and the OSU was found to be comparable to cadaveric temporal bone training (174). In the same study,

construct validity was assessed but not established by comparing participants with varying levels of surgical experiences.

Current state of research in VR temporal bone surgery training

Face validity was not achieved by all the aforementioned VR temporal bone simulators, yet content and/or construct validity was. Increasing realism for the benefit of face validity can increase the cost of the VR simulator, and does not guarantee skill transfer (153, 165). In each of the studies on content validity, varying metrics were used for assessment. In a systematic review of simulators in Otolaryngology, Arora et al. noted that there needs to be a development of standardised metrics and a definition of expected performance objectives in order to further curriculum development in VR simulation training (25). This challenge is not unique to VR temporal bone simulation, and standardised curriculum development continues to remain a barrier to the implementation of VR simulation in surgery in general (142). The review by Arora et al. also highlights that despite the clear evidence for validation of VR simulators of cortical mastoidectomy in the 12 studies presented, none had investigated the possible extension of training to more complex temporal bone surgery (175). To the author's knowledge, to date there are no known temporal bone simulators that teach beyond an extended cortical mastoidectomy.

Points of consideration for using virtual reality simulation in surgical training

Skill Retention and Transfer

A critical question when considering the use of virtual reality simulation is the effectiveness of the training to 'real life' outcomes or acquisition and transfer of technical skills. As evidenced above in the validation studies, VR simulation in cortical mastoidectomy is successful in providing skill acquisition in the short term as evidenced by performance during practice sessions. Secondly, it is important to find out whether those who have learned skills in VR simulation are able to retain these skills and transfer them to real-life surgical performance. Several studies have assessed skill retention after VR simulation training in laparoscopic surgery (176-179) with variation in findings. Maagaard et al. found novices to have retained laparoscopic skills at 6 months after training without any exposure to performing the procedure in the interim time (176), while Sinha et al. and Stefanidis et al. found only partial retention of surgical skills (178, 179). Bjerrum et al. went further to explore the possible factors for retention and evaluated the use of instructor feedback on skill retention but found no benefit of this (177). Skill retention is not consistently commented on in virtual reality simulation studies and current understanding of the variables related to skills retention are based on more general studies in education (180). One variable that is particularly relevant to VR simulation training is the sequence of practice with the common variations of massed and distributed practice sessions. Massed practice simulation programs provide all training sessions within a short time frame (usually a day) and distributed practice simulations programs provide sessions spaced in time. After finding an accelerated learning curve in medical students performing mastoidectomy with distributed practice as compared to massed practice (154), Andersen et al. went on to evaluate the effect of practice sequence on retention of mastoidectomy skills at 3 months after simulation training. There was no significant difference in the primary outcome of end product performance between groups (157). This finding suggests that although there is no clear superior style of sequencing of training, VR simulation training is successful in skill acquisition immediately after training as well as facilitating retention of surgical skills after a period of non-practice.

Complementary to the discussion on skill retention is the transfer of skills to clinical scenarios with the specific aim to evaluate the effect VR simulation training has on clinical outcomes. Dawe et al. published an updated systematic review that commented on all surgical simulator studies that compared clinical outcomes from all forms of simulation training to traditional training methods (181). The 27 randomised control trials form a strong body of evidence that simulation training improves real-life performance as evidenced by improved overall performance, shorter procedural time, greater procedural success rate (completion or competency) and fewer intraoperative errors (181). Of the studies included in the systematic review, two studies looked at the effect of VR simulation on intraoperative errors (182, 183). Ahlberg et al. found a significant reduction of total number of surgical errors throughout the procedure of cholecystectomy in participants trained with proficiency based VR simulation training (182). Similarly, Cosman et al. found a reduction in intraoperative errors as defined by an expert error performance scale in participants who underwent VR simulation training (183). However, whether this benefit can be extrapolated to otolaryngology simulators is not yet clear; in a systematic review of VR simulators in otolaryngology, Piromchai et al. (184) did not identify any studies that had evaluated patient clinical outcomes after VR simulation training.

Feedback

Although feedback may intuitively be considered a necessity in surgical education, there have been conflicting results in the benefit of feedback in skills acquisition for practical surgical tasks using simulation-based training (185-187). There are multiple theories that hypothesise the reason for inferior performance after feedback. Of these, the more commonly studied is the 'guidance hypothesis' which theorises that constant concurrent feedback leads the student to depend on feedback and influence performance when feedback is discontinued (188, 189). This theory has been evaluated in the setting of simulation training; by reducing the frequency of delivery of concurrent feedback, Stefanidis et al. found a non-inferior performance of medical students using a laparoscopic simulator trainer when limited feedback was employed (190). Similarly, Wierinck et al. found a similar performance of dental students with continuous feedback or 66% of feedback, this trend was seen both immediately after training and at a 4 month follow up (191).

Similar contention exists with regards to the optimal stage of simulator training for feedback provision. The two most common variations of timing in simulation training is concurrent (during simulation) or terminal (at the end of the procedure). While the effectiveness of both variations have had differing reports (192-194), the pooled results of these studies as presented by Hatala et al. in a metaanalysis showed no significant difference in either the immediate skills outcomes or when assessed at 5 days after training. However, there was an improved retention of skills at 1 week (192, 193) and 1 month with terminal feedback (194) suggesting a benefit in retention when terminal feedback is used. Surprisingly, there is minimal evidence demonstrating the benefit of combining terminal and concurrent feedback. In a limited randomised control trial of eight Obstetrics and Gynaecology residents, Kahol et al. compared terminal feedback to concurrent and terminal feedback in a laparoscopic simulator and found a statistically significant improvement in those using the combined feedback (195). To the author's knowledge, this is the only study to date that has assessed combining concurrent and terminal feedback; unfortunately, this study did not include an effect size.

Goal orientation and the learning curve of virtual reality simulation

In a paper on optimising learning using surgical simulators, Cannon-Bowers et al. argue that simulators should be designed to focus on mastery learning (the acquisition of skills) over performance-prove

learning (where the student proves their ability) (196). Of relevance to surgical training, mastery oriented goals have demonstrated to improve user adaptability to more complex tasks (197). In the updated systematic review by Dawe et al., it was noted that an advantageous development in recent surgical simulator studies has been that performance skill targets or objectives are predefined in 19 of the 27 studies included (181). The inclusion of a performance goal has been termed proficiency based virtual reality simulation, and often uses a mean score of expert performance as the performance goal. Ahlberg et al. evaluated this style of goal orientation in simulation in a study of 13 surgical residents who were randomised to receive proficiency-based training or no simulation training prior to performing laparoscopic cholecystectomies (182). Virtual reality simulated training was considered completed once the participant was able to perform at the level of the mean score of the expert performance on a range of tasks. Results showed that those who underwent proficiency based training had significantly fewer errors in their first 10 laparoscopic cholecystectomies performed on real life patients as discussed in the previous section (182). In addition to showing an improvement in clinical outcomes, this study confirms the benefit of proficiency-based training but lacks the ability to show a benefit as compared to simulation training without performance goals. To the author's knowledge, there have been no studies to date that directly compare proficiency-based simulation training to simulation training without objective goals and this is an area for future research.

Proficiency based simulation has also been used to develop curricula for whole procedures such as laparoscopic cholecystectomy. Aggawarl et al. confirmed construct validation on a VR simulator that used step-wise task modules to teach laparoscopic cholecystectomy (198). As with other proficiency-based studies, they used the mean score of experts to define competencies. A similar approach was used by Arora et al. in a study of proficiency based training and development of a curriculum for extended cortical mastoidectomy (175). In both these studies, the benchmark performance was based on the mean performance of experienced surgeons at their second attempt on the VR simulator (198) (175). The rationale for defining this benchmark performance is founded on a previous study that verified the learning curve for participants at varying levels of experience who had not previously used VR simulation training (199). Experienced surgeons reached a plateau of time to complete the procedure at the second repetition and surgical error and economy of movement in the first repetition. In contrast, novice surgeon having previously performed less than 10 laparoscopic cholecystectomies, plateaued at the seventh and sixth repetitions respectively. The lack of a learning curve for surgical error of movement economy seen in the experienced surgeon group is an important finding as it demonstrates that no previous experience in a virtual reality simulator is required to assess performance using this media. Therefore, improvements in performance assessed using a virtual reality simulator are likely to be translatable to real life experience.

Assessment

Similar to using the proficiency-based simulations to develop a curriculum, VR simulators lend themselves well to integration of objective assessment tools. Despite this, there are few tools that have been developed to assess temporal bone surgery. The objective structured assessment of technical skills (OSATS) is a tool that has been adapted and validated in multiple surgical specialties (200-203). The OSATS tool is divided into three areas of performance – a task-based checklist, a global rating scale and a final judgement (pass/fail). One limitation of this tool that has been expressed is that the end product may not be sufficiently evaluated (204). The Welling Scale has been validated as an end product assessment tool in mastoidectomy (205) and has been expanded to include a more detailed assessment of drilling style and a global rating scale (152, 165). An alternative adaption has

been produced by Wan et al. after collaborating with American Otolaryngologists. They devised a “Cross-Institutional scale for temporal bone dissection” assessment tool amalgamated from multiple surgical training programs as well as the surgical simulator from Stanford University (206). Similar to the content of temporal bone simulators, these tools are mostly specific to mastoidectomy with the exception of one criteria of the cross-institutional tool which briefly defines exposure of the facial recess (206).

More recently, Piromchai et al. developed and validated a competency tool for cochlear implant surgery. The assessment tool has a global competency scale adapted from those previously presented (152, 165, 202, 205) and a task based checklist of surgical steps synthesised from a standard otology textbook (207). In a study of seven residents and seven experts, this assessment tool was found to have a high level of construct validity with a significant difference in scores between experts and residents and high intra-class coefficients. These results suggest that cochlear implant surgery is an appropriate procedure to be considered for proficiency-based training.

Virtual reality simulation in temporal bone anatomy education

To the author’s knowledge there are only two studies that have investigated the use of virtual reality simulation training in temporal bone anatomy. Fang et al. describe the use of a haptics enabled, stereoscopic 3D temporal bone simulator as an anatomy trainer (50). Seven medical students participated by performing virtual reality mastoidectomy surgery after learning ear anatomy by means not described in the study. Students completed a survey before and after the simulation session including a technology acceptance model questionnaire as well as a 3-point Likert scale of understanding of 5 core structures of the temporal bone. There was a significant improvement in the self-reported comprehension of anatomical structures and positive responses in the technology acceptance model questionnaire, and all students reported an increase in interest in otology. Despite the limitations of a small participant group and self-assessment of primary outcomes, this study indicates the benefit of virtual reality simulation in training basic, factual based temporal bone anatomy. Importantly, this study also showed the benefit of simulation training in improving interest in otology as a discipline.

These results complement the results of a previous study by Nicholson et al. where 61 students were given a 2D tutorial on ear anatomy before being randomised to an online tutorial with monoscopic 3D or 2D middle and inner ear model (51). The monoscopic 3D model was segmented from a magnetic resonance imaging scan of a human temporal bone and allowed for image manipulation (zoom and rotation). The participants were required to meet an objective of ear anatomy understanding on a preliminary anatomy quiz before commencing the studied module. They were also assessed on their visual-spatial skills prior to commencing the tutorial and all participants underwent an anatomy quiz of 15 questions to assess the understanding of 3D relationships between ear structures after completing the module. The group allocated to the 3D enabled tutorial had significant improved comprehension of ear anatomy relations than that of the 2D group with significantly lower mean time to complete the final quiz. There was no difference between groups in visual-spatial skills. This study gives further evidence that a virtual reality 3D model of the temporal bone is effective in training both anatomy comprehension and understanding of anatomical relations. However, both these studies share the limitation of exposing students to only partial sections of anatomy training; neither module was significantly interactive nor objectively assessed the benefit of this style of training in understanding otology as a clinical discipline.

Points of consideration for using virtual reality simulation in temporal bone anatomy training

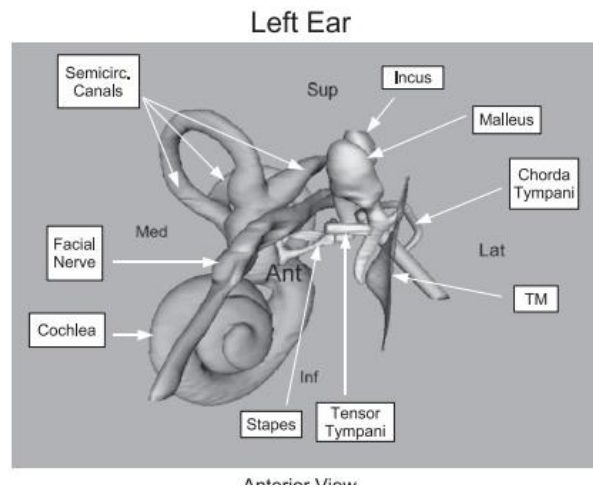


Figure 1.5: 3D reconstructed ear model used in educational module (from Nicholson et al 2006).

Clinically oriented anatomy

Dangerfield et al. describes a novel approach to anatomy teaching in The University of Liverpool's clinical skills program which incorporates clinical education and skills training with relevant anatomy (208). This style of clinically relevant anatomy training was later investigated in a longitudinal study by McBride et al. and was found to result in significant retention of knowledge, remaining above 90% at the 4th year of medical school (47). The authors describe the components of the course to include a clinical case and associated anatomy prosection and radiological imaging. Brinke et al. devised an alternative but equally successful clinically oriented anatomy module where laparoscopic dissection was integrated into an anatomy module on the inguinal region (209), hypothesising that manual interaction improves understanding of complex anatomy. In addition, of the three study arms, the participants who underwent 3D anatomy training alone scored higher in the anatomical identification test than the group that received 3D and 2D anatomy training and those that received 2D anatomy training alone. Despite the limitation of a small sample size, this study gives strength to the argument for integrating surgical training with clinical anatomy training, bridging the gap between medical school anatomy training and post-graduate, specialty specific anatomy and surgical training.

Display technology in simulation anatomy training

In a meta-analysis on the effectiveness of 3D visualisations in anatomy education, Yammine et al. highlight the benefit of the 3D virtual reality simulators in understanding factual and spatial relationships of anatomical structures, with the ability to view the anatomical structure from multiple viewpoints (210). There are multiple display technologies with varying complexity and cost that have been used in anatomy education modules (211). The more common visualisations are monoscopic 3D and stereoscopic 3D. Monoscopic 3D uses size, shading and texture to replicate depth cues (212, 213). On the other hand, stereoscopic 3D requires glasses that shutter display from alternating eyes to provide a binocular depth cue (213, 214). Less common are the technologies of augmented reality (where digital information is displayed in the context of a real-world object) and auto-stereoscopic (where depth perception is afforded with specialised displays without the need for glasses).

With the financial pressures facing anatomy educators, emphasis needs to be placed on the display technology providing an effective and cost-effective adjunct to traditional training methods. One benefit of monoscopic 3D is that it requires no specialised equipment, allowing it to be cost effective (211). Both monoscopic 3D and Stereoscopic 3D devices have been shown to improve anatomic understanding with a positive perception of student participants as compared to 2D or traditional teaching (210, 211, 215, 216).

In a study of 156 medical students, Muller-Stich et al. compared monoscopic and stereoscopic 3D display technologies used to teach the anatomy of the human liver (217). All participants were given a lecture on liver anatomy in both 2D and monoscopic 3D prior to randomisation. After randomisation, participants were assigned to 2D, monoscopic 3D and stereoscopic 3D models which were made available to aid in answering 11 anatomy and clinical related questions. The authors concluded that 3D visualisations were superior in allowing identification of liver anatomical structures, without a significant difference between the monoscopic and stereoscopic platforms. To the author's knowledge, this is the only study to date that directly compares the use of monoscopic and stereoscopic 3D anatomy education. Indeed, Hackett et al. concluded that research in stereoscopic 3D for anatomy education is underrepresented despite the increasing availability of stereoscopic 3D platforms; They argue that further studies are required to directly compare the visual technologies of monoscopic and stereoscopic 3D (218).

Conclusions

Optimising hearing outcomes in cochlear implant surgery is an important issue in making cochlear implants available for a wider range of recipients. It was observed through various studies that preservation of hearing outcomes is closely related to reduced trauma during insertion. As such, an exploration of the causes and methods of reducing the trauma of insertion is vital. Existing literature suggests that anatomical, procedural and training factors contribute to the trauma of cochlear implant surgery. In addition, with the changing environment for surgical training, methods for training surgeons to be experts must be reformed.

Virtual reality simulation is an efficient and effective platform on which surgeons can be trained as a supplement to traditional, apprenticeship-based surgical training. Despite a growing body of evidence that identifies the benefits, validity and applicability of VR in surgical training, there have been few studies that explore its use in advanced surgical procedures such as cochlear implantation. In addition, there are ongoing discussion on how to maximise training, retention and transfer from simulated surgery.

Furthermore, temporal bone anatomy education forms the basis of surgical training and its method of delivery suffers similar time and resource pressures to those faced by specialty training. Limited evidence indicates potential for the use of virtual reality simulation in temporal bone anatomy education. Integration of clinically orientated material and consideration for display technology are areas identified as lacking in the current literature.

An expert cochlear implant surgeon has an excellent mental representation of the anatomy of the cochlea and minimises electrode insertion trauma by assessing the anatomical variations for an individual patient, selecting an appropriate electrode and appropriately preparing the cochlea for implantation via cochleostomy or round window membrane insertion. With the aim of hearing preservation, cochlear implant electrode designs have evolved, and some models are now using a stiff and straight insertion tool. These electrode designs continue to rely on excellent surgical technique to

optimise results. While the fundamental procedure of electrode insertion remains unchanged, the evolution of these electrodes prompt reassessment of the approach to the facial recess and cochlea. It remains unclear how the path of the cochlear implant electrode into the cochlea affects the region of the facial recess that needs to be exposed.

Chapter 2: Virtual reality simulation in clinically oriented temporal bone anatomy education

Introduction

Anatomy education in medical training is adapting to a changing environment of reduced contact hours concurrent with ensuring adequate education standards(3). The trend toward presenting medical education in a clinically oriented manner has extended to the education of medical anatomy (208). Virtual reality simulation has been shown to be beneficial in training other areas of anatomy such as neuroanatomy (219) and has been successfully adapted to clinically orientated hepatic anatomy education (220). VR is also widely accepted as beneficial in the training of basic surgical procedures of the temporal bone (151-153, 155-157, 221). Despite this, there has been limited investigation of virtual reality simulation in temporal bone anatomy education (50, 51). In addition, to the author's knowledge there has been no previous studies that have included clinically relevant anatomy dialogue in simulation temporal bone anatomy education.

Furthermore, the optimal technology for displaying three dimensional (3D) virtual reality anatomy modules is indeterminate (218). Two commonly used technologies are monoscopic 3D and stereoscopic 3D. Stereoscopic 3D has the benefit of depth perception, while monoscopic 3D requires no additional virtual reality headset/glasses. While both display technologies have been investigated in previous anatomy simulators, there are limited studies comparing the two directly (217).

In this chapter, this gap in literature is addressed by developing and investigating a clinically oriented temporal bone anatomy education module. The module was assessed with an initial pilot study comparing the module displayed in stereoscopic 3D to a 2D presentation. A further study was performed comparing stereoscopic 3D, monoscopic 3D and a 2D presentation.

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Development and Validation of a Virtual Reality Tutor to Teach Clinically Oriented Surgical Anatomy of the Ear

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Abstract—Virtual reality (VR) is being increasingly used in medical education. However, investigations into its effectiveness in this field have yielded mixed results, indicating that no general conclusions can be drawn in this regard. Therefore, the suitability of a system to teach a given task has to be investigated on a case-by-case basis. In this paper, we focus on teaching clinically oriented surgical ear anatomy, as it is important to provide a well-rounded view of ear anatomy as a foundation for understanding clinical surgery. Although there are some VR systems that teach basic ear anatomy, for example, identification of structures and spatial relationships, to our knowledge, those that deliver a complete clinical understanding of ear anatomy do not yet exist. As such, we discuss the design and development of a 3D interactive VR tutor with integrated haptic capability to teach clinically oriented surgical anatomy of the ear and establish its effectiveness through a user study.

Keywords—Anatomy Education, Virtual Reality, Simulation-Based Training;

I. INTRODUCTION

Traditionally, cadaveric dissection and didactic lectures have been the sole pedagogy in anatomy education [1]. However, in recent times, there have been efforts to replace conventional methods of anatomy education with more modern methods such as model substitutes and technology [2], [3]. Within this context, VR has become popular as a platform for training anatomy. Compared to didactic training, VR offers a more engaging and interactive environment akin to that of serious games, which have been proven to be effective in increasing learning [4]. In comparison to cadaveric dissection, VR is more accessible, risk and disease free, and is repeatable. As no material replacement is required, the long-term cost is low. Rare and complex pathologies that are not easily found in practice can be included in VR to offer a more complete learning experience. It also allows the integration of lecture-like instructions into its environment so that advantages of both forms of traditional training can be combined to support independent learning. As such, VR has been identified as an ideal platform for teaching anatomy.

Solyar et al. [5] investigated the effectiveness of a VR endoscopic sinus surgery simulator with haptic feedback as a tool for teaching paranasal sinus anatomy. They showed that students trained on this VR simulator performed signifi-

cantly better than a textbook group in identifying anatomical structures and took less time to complete the task. Pahuta et al. [6] showed that a virtual fracture carving simulator can be used to teach the anatomy of an associated both-column acetabular fracture. They compared the performance of 3 groups: control, sawbones, and VR, testing their performance using a fracture line-drawing task evaluated for 19 anatomic relationships. The VR group performed better than both the control and sawbones groups.

Hariri et al. [7] evaluated the effectiveness of teaching shoulder anatomy using an arthroscopy simulator that supported haptic feedback. They found that compared to textbook learning, no significant improvement in anatomy knowledge was acquired through VR learning. Garg et al. [8], [9] investigated the effectiveness of teaching wrist-bone anatomy using 3D VR when compared to a presentation of a small number of views consistent with the approach taken by most anatomical atlases. They came to a mixed conclusion that the potential for dynamic display of multiple orientations provided by computer-based anatomy software may offer minimal advantage to some learners and may disadvantage learners with poorer spatial ability.

As these mixed observations indicate, it is not practical to draw broad conclusions regarding the effectiveness of VR in anatomy education. Rather, it is a subjective matter that has to be investigated on a case-by-case basis. Our focus in this paper is teaching anatomy of the temporal bone and middle/inner ear. As Nicholson et al. [10] point out, the complexity of the middle and inner ear, coupled with the small size of its anatomical structures, creates many obstacles to teaching ear anatomy with traditional instructional techniques. As such, it is important to investigate alternate techniques such as VR. Although there exist many VR simulators developed and validated to train ear surgery [11], [12], the use of VR in teaching ear anatomy is not common.

Nicholson et al. [10] constructed an interactive model of the ear from a magnetic resonance imaging (MRI) scan of a human cadaver ear. They showed that students who trained on this interactive model were significantly better in their knowledge of 3D relationships within the ear when compared to those who trained on a non-interactive version.

Feng et al. [13] discussed how a haptically enabled VR surgery simulator can be used to teach ear anatomy. They showed that students' comprehension of ear anatomy was significantly improved after VR training.

However, these existing VR systems only teach the fundamentals of anatomy, such as identification of anatomical structures and their spatial relationships, but not a clinically oriented perspective that is crucial in many sub-specialties of medicine such as radiology and surgery. To overcome this limitation, we introduce a VR tutor that provides training on clinically oriented surgical anatomy and establish its effectiveness through a user study.

II. VR TUTOR FOR TEACHING CLINICALLY ORIENTED SURGICAL EAR ANATOMY

A. VR environment

For the development of the VR tutor, we used the University of Melbourne VR temporal bone surgery simulator (see Figure 1). This simulator comprises a computer running a virtual model of a temporal bone generated using a micro-CT scan of a human cadaver ear. A haptic device provides tactile feedback and is reflected in the virtual world as a drill. The anatomical structures (such as the dura, sigmoid sinus, and facial nerve), along with the temporal bone, are rendered with different visual and tactile properties. The impression of depth (or stereoscopic 3D vision) is achieved through NVIDIA 3D vision technology. A MIDI controller is used as a convenient input device to change environment variables such as magnification level and burr size.



Figure 1: VR temporal bone surgery simulator.

B. Principles behind the design of the VR tutor

In their call for the modernization of anatomy education, Sugand et. al [1] compiled a set of 5 modalities to be used when designing optimal learning content for teaching anatomy. We used these modalities as guidelines in developing our VR tutor.

1. Dissection/prosection: Active observation and participation in cadaveric dissection has been identified to help the understanding of three-dimensional (3D) structures through curiosity and self-exploration [14]. Lempp [15] sums up dissection as an opportunity to reinforce familiarization and respect for the body and integration of theory into clinical practice. Thus, Sugand et al. [1] suggest dissection/prosection on cadavers or plastinated cadaveric specimens as important in teaching anatomy. However, they also recognize the advantages of using modern technology to supplement this form of teaching. As such, we developed the VR anatomy tutor to allow self-exploration through interactive dissection of a virtual temporal bone. Integrated haptic technology allows the student to experience the tactile sensation of drilling. Stereoscopic 3D makes it possible to understand the spatial relationships of anatomical structures and the surgically relevant regions of the temporal bone.

2. Interactive multimedia: The future of anatomy teaching must rely more on visual aids outside the dissection room [16]. The rationale is that students will naturally forget topics covered in dissection class and resources like web-streamed lectures and instructional videos could prove vital for revision [1]. The VR tutor presents anatomy knowledge in a fully-interactive fashion that supplements traditional learning and supports self-guided exploration. The student interacts with the system in the form of drilling. Deeper regions and anatomical structures are uncovered when bone is drilled. The system provides visual cues in the form of coloured regions and text, as well as auditory information explaining the functions and importance of regions and anatomical structures as the student performs a dissection.

3. Procedural anatomy: Practicing clinical procedures requires thorough knowledge of anatomy on either cadavers or plastic models [1]. Thus, it is important to teach anatomy in the context of common procedures. We implemented the teaching of procedural anatomy in the VR tutor by defining surgically relevant regions of the temporal bone and anatomical structures, presenting a list of these regions and structures with corresponding colours that the student has to find through dissection, and explaining the clinical/surgical importance of each while the student interacts with it. The list of regions and structures to be identified, along with the explanations, is presented in a way that takes the student along a step-wise approach to ear surgery. As such, the VR tutor is designed to teach not only simple ear anatomy, but also the principles of temporal bone surgery.

4. Surface and clinical anatomy: Surface and clinical anatomy is applicable to patient care as anatomical landmarks and clinically relevant structural outlines are defined [1]. Although it was observed that multimedia supplements cannot substitute the practical experience obtained through handling patients [17], this is impractical when teaching anatomy such as that of the ear which requires dissection. In

the VR tutor, surface and clinical anatomy is taught through visual highlighting of surgically relevant regions, representation of critical anatomical structures, and explanations of their clinical and surgical relevance.

5. Medical imaging: Radiology education offers in vivo visualization of anatomy and physiology as well as insight into pathological processes [18]. Although radiological images or anatomical models cannot substitute the benefits of conventional dissection, hybrid teaching modalities would undoubtedly contribute to better understanding and retention [1]. The VR tutor does not directly offer the capability of teaching anatomy using radiological images. However, the virtual model used in the VR tutor is an anatomically correct model generated from a micro-CT scan of a human cadaver ear. As such, the student receives an understanding of the detail and quality of a 3D rendering of a micro-CT image.

C. Design of the VR tutor

The VR tutor has the following features, designed to support the teaching of clinically oriented ear anatomy.

1. Identification of surgically relevant areas of the temporal bone: The surgically relevant regions of the temporal bone are highlighted in the VR tutor in different colours (see Figure 2). When a highlighted region is being drilled, the text at the top of the screen identifies what it is. Regions deeper within the temporal bone can be uncovered by drilling away the regions on the surface.

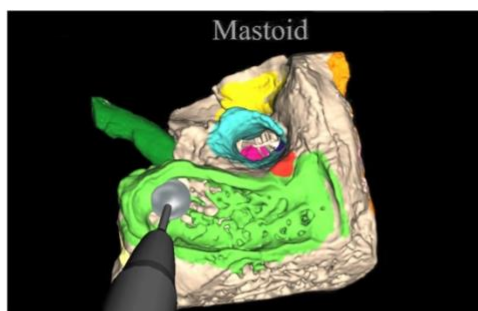


Figure 2: Visual representation of important regions of the temporal bone in different colours.

2. Explanations of the clinical and surgical relevance of areas of the temporal bone: To explain the clinical/surgical relevance of a temporal bone region, when the student drills that region, the VR tutor plays a pre-recorded audio. No other audio is played during this time even if the student moves on to another region. To avoid the audio being repeatedly played while drilling a region, a time interval is defined within which time, the audio that was played before is not replayed. Once this time elapses, the audio will be

repeated when drilling in the same region. However, the student has the option to override this and play the audio for the region being drilled by pressing a button.

3. Representation of the 3D spatial relationships of anatomical structures: Each anatomical structure of the ear is rendered in the VR tutor by a different colour close to its actual colour. The temporal bone can be made transparent to view the underlying anatomical structures without dissecting the bone. This allows for easy access to structures deeper within the temporal bone. When the student moves the drill within a pre-defined distance of a structure, the text field at the top of the screen shows its name (see Figure 3).

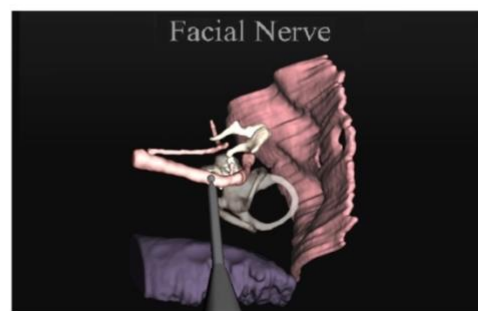


Figure 3: Identification of anatomical structures in the transparent mode when the bone has been removed from view.

In the normal mode, where the bone is visible, the student can uncover the underlying anatomical structures by dissecting the bone. Similar to the transparent mode, the text field at the top of the screen identifies the structure when drilling near it (see Figure 4).

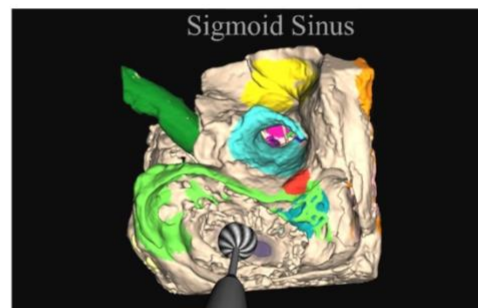


Figure 4: Identification of anatomical structures by the VR tutor in the normal view of the temporal bone.

If the drill is close to more than one anatomical structure, the names of all of the structures that are close are displayed

in the text. By reducing the size of the burr, the student can separately identify anatomical structures that are close together such as the ossicles (incus, malleus, and stapes).

4. *Explanations of the clinical relevance and functionality of anatomical structures:* Similar to how the importance of a surgically relevant region of the temporal bone is taught, the VR tutor plays a pre-recorded audio to explain the functionality and relevance of each anatomical structure. During this time, no other audio is played. Once the audio for a structure has been played, it is not repeated within a given period of time. If there are multiple structures close to the drill, no audio is played, to avoid confusion. The student has the option of hearing the audio of a structure by bringing the drill close to it and pressing a button at any time.

III. EVALUATION OF THE VR TUTOR

To evaluate the effectiveness of the VR tutor and identify any limitations, we conducted a pilot study. Ethics approval for this study was obtained from the Royal Victorian Eye and Ear Hospital Human Research Ethics Committee (#17-1313H). The participants of this pilot study were medical students and junior doctors. The study conducted was a randomized trial that compared the effectiveness and usability of the VR tutor against a 2D non-interactive version that presented the same content. Figure 5 illustrates the study design. Two questions were addressed in this study: 1) Is the content of the VR tutor effective? and 2) Is the interactivity of the VR tutor a significant contributor to its effectiveness?

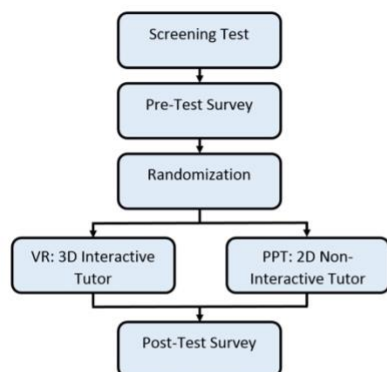


Figure 5: Design of the pilot study.

Written consent was obtained from all participants and a screening test was conducted to determine the knowledge level of the participants. This test consisted of 3 intermediate questions on the anatomy of the ear. To ensure that the knowledge level of the participants was uniformly basic,

participants who answered all questions correctly were excluded from the data analysis, although they were allowed to participate in the study itself. Twenty one participants were recruited and one was excluded based on this criteria.

After the screening test, a pre-test survey was conducted to identify the demographics, relevant experience (for example, gaming experience), confidence in knowledge of ear anatomy, and study preferences of the participants. Then, they were assigned to one of 2 groups using block randomization. The first group (VR) was asked to find a list of anatomical structures and temporal bone regions by interacting with the 3D VR tutor. The second group (PPT) was presented with the same information but in the form of a PowerPoint presentation of 2D screen shots taken from the VR tutor along with the same audio explanations. Participants were not made aware of what the other group did. No time limits were imposed and the participants were allowed to learn as they preferred.

After the training, participants answered a post-test survey which consisted of questions in relation to their level of confidence in their knowledge of ear anatomy, their perspective of the teaching method, and knowledge of ear anatomy. The two former types were based on a 5 point Likert scale with scores ranging from 1: 'strongly disagree' through 3: 'neutral/neither' to 5: 'strongly agree' and had 7 questions. The latter comprised 50 questions on categories used in previous studies [13], [10]: general ear anatomy (32) and spatial relationships (13), as well as an additional category: clinical anatomy and diagnostics (5). All questions were approved by an expert otologist.

The collected data was analyzed between groups using Kruskal-Wallis tests, so as to avoid assumptions of normality. Results were considered to be significant at a confidence level of 95% ($p < 0.05$).

The male:female ratio of the 20 participants was 2:3. Medical student to junior doctor ratio was 7:13. The median age of the participants was 25 years. The median year for medical students was year 5 while for junior doctors, it was postgraduate year (PGY) 2. Only one participant was left handed. Relevant background information collected in the pre-test survey was compared between groups. The results are given in Table I. At the start of the study, the confidence level of the participants on their knowledge of ear anatomy was low with no significant difference between groups. The study style preference of the two groups was similar between groups except in one respect. The participants in the PPT group were significantly more open to studying anatomy alone. No significant difference was observed in any of the categories of relevant experience.

The results of the post-test survey are shown in Table II. Both groups scored relatively high in the knowledge tests. No significant differences between groups were observed with respect to any of the 3 modalities of anatomy knowledge tested. The confidence level of the participants was

Table I: Results of the pre-test survey. The median and inter-quartile range of the two groups, along with comparison results are shown. Results that are significantly different between groups are given in bold.

	VR: Median (IQR)	PPT: Median (IQR)	Comparison
Confidence level			
I feel confident in my knowledge of temporal bone and inner ear anatomy	2(1)	2(0)	p = 0.676
I understand the temporal bone and inner ear as a three dimensional structure	2.5(2)	3(1)	p = 0.845
Rating of my understanding of temporal bone anatomy	2(2)	2(1)	p = 0.968
Study style preference			
I prefer to learn anatomy alone	2(1)	4(1)	p = 0.019
I prefer to learn anatomy in a group	4(0)	3(2)	p = 0.325
I find textbooks revision an effective way to learn temporal bone and inner ear anatomy	3(2)	3(1)	p = 0.809
I find didactic lectures an effective way to learn temporal bone and inner ear anatomy	3(0)	3(1)	p = 0.293
Relevant experience			
Previous mastoid surgery experience (as assistant)	0(0)	0(0)	p = 0.957
Previous mastoid surgery experience (as observer)	0(1)	0(2)	p = 0.657
Previous virtual reality temporal bones drilled	0(0)	0(0)	p = 0.317
Gaming experience	2(1)	1.5(1)	p = 0.262

seen to be significantly better in the VR group after training. Perception of the participants on the teaching methods was high for both groups, with respect to all the tested categories. However, there was a significantly higher level of appreciation in the VR group as to the effectiveness of the tutor in teaching ear anatomy. According to the results, the VR tutor is also more likely to be used by the participants again, when compared to its 2D counterpart.

IV. CONCLUSION

According to the results of the pilot study, students in both groups scored relatively highly in terms of knowledge in basic anatomy, spatial relationships, and clinical functionality and diagnosis. Considering that their initial level of knowledge was basic, as ensured by the screening criteria, the test results show a notable level of learning after training. This indicates that the content of the VR tutor (both in its 3D interactive form and when presented via 2D screen shots in a less interactive presentation) is suitable for teaching clinically oriented surgical anatomy of the ear.

As there were no significant differences in knowledge between groups, this may lead us to believe that neither the 3D nature of the VR tutor nor its interactivity had added value to the acquisition of knowledge. This is consistent with the findings of Garg et al. [8], [9] who concluded that the potential for dynamic display of multiple orientations provided by computer-based anatomy software may offer minimal advantage. However, this may be a premature conclusion due to several possible reasons. First, as Nicholson [10] suggests, the mixed results observed in literature as to the effectiveness of VR in teaching anatomy may be due to issues in the study design and not the VR systems themselves. This is applicable to our situation as well since some effects may have been present in the data that were too small to be detected due to limited participant numbers.

Although the two groups were relatively similar in most

aspects that were tested for in the pre-test survey, there was a significant difference in the study style, with the PPT group showing more of a preference for studying alone than the VR group. This may mean that the PPT group had an advantage in that they were better at using self-directed teaching similar to what the VR tutor and its less interactive counterpart offered. The purely 2D nature of the paper-based post-test may also have favoured the PPT group.

Furthermore, Garg et al. [8], [9] observed that dynamic display and multiple orientations may be disadvantageous to students with poorer spatial ability. As this pilot study did not test for such physical limitations of students like spatial ability, it is not possible to say to what extent they may have played a role in the observed results.

Both groups were seen to have highly positive perceptions of the system. However, the VR group was significantly more confident in their knowledge after training, thought the VR tutor was more effective in teaching anatomy, and were more likely to use the system again. As better user perception of a teaching system leads to learner motivation and continued usage, it is an aspect that may be as important as its effectiveness in teaching the subject matter. As such, we can infer that the VR tutor is a successful tool for teaching clinically oriented ear anatomy.

A more comprehensive study that resolves the issues identified in the pilot study (with higher participant numbers, tests for detecting spatial ability, stratified randomization, additional post-tests for determining knowledge of 3D anatomy such as spotter tests on cadavers or 3D models etc.) will have been conducted in the future so that more concrete conclusions can be drawn as to the effectiveness of the VR tutor in teaching ear anatomy. More data including metrics such as time to learn and detailed participant interviews should be collected to gain a deeper understanding of the capabilities of the different aspects of the tutor.

Table II: Results of the post-test survey, showing the median and inter-quartile range of the two groups, along with comparison results. Results that are significantly different between groups are given in bold.

	VR: Median (IQR)	PPT: Median (IQR)	Comparison
Knowledge of ear anatomy			
Basic anatomy (out of 32)	15(9)	18(7)	p = 0.677
Spatial relationships (out of 13)	7(4)	6.5(4)	p = 0.848
Clinical anatomy and diagnostics (out of 5)	2(2)	3.5(3)	p = 0.203
Confidence level			
I feel confident in my knowledge of temporal bone and inner ear anatomy	4(1)	3(0)	p = 0.048
I understand the temporal bone and inner ear as a three dimensional structure	4(0)	3(1)	p = 0.008
Perception of usefulness			
I prefer to use this teaching method alone	4(1)	3(2)	p = 0.250
I prefer to use this teaching method in a group	3(2)	3.5(1)	p = 0.845
I found this module easy to use	4(0)	4(1)	p = 0.213
I found this an effective way to learn temporal bone and inner ear anatomy	4.5(1)	4(1)	p = 0.003
I would use this way of learning anatomy again	4.5(1)	3.5(2)	p = 0.009

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Development of a virtual reality clinically oriented temporal bone anatomy module with randomised control study of three-dimensional display technology

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ABSTRACT

Objective To investigate the effectiveness of a virtual reality (VR), three-dimensional (3D) clinically orientated temporal bone anatomy module, including an assessment of different display technologies.

Methods A clinically orientated, procedural and interactive anatomy module was generated from a micro-CT of a cadaveric temporal bone. The module was given in three different display technologies; 2D, 3D with monoscopic vision, and 3D with stereoscopic vision. A randomised control trial assessed the knowledge acquisition and attitudes of 47 medical students through a pretutorial and post-tutorial questionnaire. The questionnaire included questions identifying anatomic structures as well as understanding structural relations and clinical relevance. Furthermore, a five-point Likert scale assessed the students' attitudes to the module and alternative learning outcomes, such as interest in otology and preparedness for clinical rotations.

Results As a whole cohort, the total test score improved significantly, with a large effect size ($p \leq 0.005$, Cohen's $d=1.41$). The 23 students who returned the retention questionnaire had a significant improvement in total test score compared with their pretutorial score, with a large effect size ($p \leq 0.005$, Cohen's $d=0.83$). Display technology did not influence the majority of learning outcomes, with the exception of 3D technologies, showing a significant improvement in understanding of clinical relevance and structural relations ($p=0.034$). Students preferred 3D technologies for ease of use, perceived effectiveness and willingness to use again.

Conclusions The developed VR temporal bone anatomy tutor was an effective self-directed education tool. 3D technology remains valuable in facilitating spatial learning and superior user satisfaction.

medical schools, Craig *et al* remarked on the under-representation of 3D technologies.⁴ Additionally, in medical education, clinically oriented anatomy education has been shown to improve knowledge retention,¹¹ motivation¹² and students' interest in pursuing a surgical career.¹³ Unfortunately, in the classroom environment, clinical integration of anatomy education can be resource intense^{13 14} and logistically challenging.¹⁵

Knowledge of the 3D complex anatomy of the temporal bone is essential in understanding the pathophysiology and management of otological disorders and forms the basis of therapeutic surgical procedures.^{16 17} In addition, a working knowledge of ear anatomy is also important to general practitioners and emergency physicians, where ear disease is often a presenting complaint.^{18 19} Although there have been several virtual reality (VR) simulators developed to train otology surgery,²⁰ there has been little work on VR simulation to facilitate learning of temporal bone anatomy. For example, Nicholson *et al* developed a 3D inner ear anatomy module from MRI images that could be manipulated through a web browser.²¹ In a randomised control study, they found that students learning in this 3D environment performed better on summative anatomical assessment than students who learnt from 2D images and text. Fang *et al* evaluated the use of an interactive 3D VR temporal bone simulator as an anatomy teaching aid.²² The seven medical students who participated reported an increased understanding of temporal bone structures, and a heightened interest in otology.

This limited evidence base suggests that 3D modules may assist training in inner ear and temporal bone anatomy. Fang *et al*'s study highlights the potential for VR training to foster an interest in otology and to benefit procedural style learning. This is echoed in Sugand *et al*, whose review of anatomy teaching emphasised that procedural and clinical anatomy are core components of an optimised approach to anatomy education.²³ In a review of 3D technologies for anatomy education, Hackett and Proctor noted that despite the beneficial results of 3D anatomy education technologies, there is a lack of literature regarding the retention of knowledge and transfer to clinical skills.²⁴ In addition, the comparison of 3D modalities (in particular monoscopic 3D vs stereoscopic 3D) for content delivery is unexplored. The aim of this study was to bridge these gaps by investigating whether a VR



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INTRODUCTION

Anatomy training in medical schools has suffered the pressures of reduced training hours^{1–4} leading to a decline in the time allocated to acquiring a breadth of anatomical knowledge.^{5–7} In order to effectively use the available time, alternatives to traditional teaching techniques such as three-dimensional (3D) visual technologies are increasingly being used. These technologies have been shown to benefit anatomy education, particularly in the reinforcement of spatial knowledge, and have reported high user satisfaction.^{8–10} However, in a review of anatomy education in Australian and New Zealand

Original research

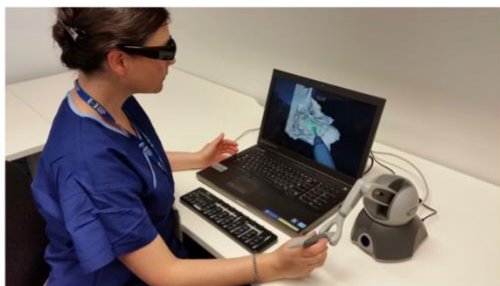


Figure 1 The University of Melbourne virtual reality temporal bone simulator setup.

3D clinically oriented, procedural and interactive temporal bone anatomy module would lead to improved knowledge, retention of knowledge and increased clinical understanding. In addition, this study compared the module's effectiveness when delivered in stereoscopic 3D and monoscopic 3D displays.

METHODS

Setting

This study used the University of Melbourne VR temporal bone surgery simulator. The experiments were conducted in a quiet simulator centre (figure 1). The simulator displayed a virtual model of a 3D cadaveric human temporal bone reconstructed from manual segmentation of a micro-CT scan. A haptic device (Sensable Phantom Omni) provided tactile interaction and feedback, and was represented in the simulation as a surgical drill. Stereoscopic 3D visualisation (providing depth perception) was rendered with NVIDIA 3D vision glasses. A MIDI device (musical instrument digital interface) controlled the zoom and drill burr size. Face validity of this simulator had previously been established.^{25–27}

The surgery simulator was adapted to create an anatomy module, for the purpose of anatomy education, by segmenting anatomically relevant structures and colour-highlighting each structure within the temporal bone (figure 2, video demonstration provided in online supplemental appendix video). The structures segmented were: mastoid, tegmen tympani, dura,

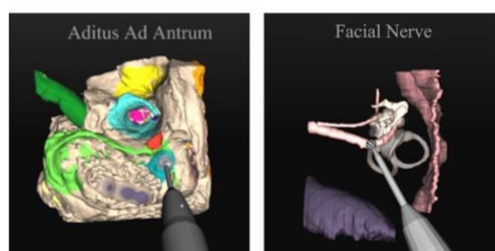


Figure 2 Screenshots of the anatomy simulator showing the highlighted virtual bone (right) and transparent bone (left). The drill shows varying burr sizes. A cursor that is used to manipulate the bone angle. Coloured highlighted bone displays anatomic structure name when it is drilled. In the transparent bone mode, anatomic structure name is displayed when the burr contacts the structure. With the display of the anatomic structure name, the corresponding audio explanation is triggered.

sigmoid sinus, spine of Henle, aditus ad antrum, facial nerve, chorda tympani, malleus, incus, stapes, cochlea, round window, oval window, stylomastoid foramen, digastric fossa, facial recess, sinus tympani, promontory, tympanic bone and scutum. In addition, a prerecorded audio was embedded to the simulator explaining the clinically oriented anatomy relevant to each structure. The content of this module was developed by a doctor in specialist training with anatomy education experience, overseen by a consultant otologist. When drilling a highlighted structure during simulation, the name of the structure was displayed on the screen and the audio accompaniment was triggered (online supplemental appendix I). The student was expected to drill away each anatomical point of interest to reveal deeper structures. In addition, the entire temporal bone could be made transparent which permitted visualisation of the deep and membranous structures (eg, ossicles, cochlea and semicircular canals).

The development of the VR module was guided by the components of 'an optimal anatomy curriculum', as proposed by Sugand *et al* for a modern and compact learning environment.²³ The system components as discussed below were introduced to ensure that this was an independent and self-guided learning environment.

Dissection/prosection

Sugand *et al* identified that dissection remains a valuable tool in aiding an understanding of anatomy in 3D. Dissection also fosters reflective education through curiosity and self-exploration.^{28 29} To this end, the anatomy module developed relied on student dissection of the VR temporal bone in order to expose clinically relevant anatomic structures. The automatically triggered audio was used in lieu of an anatomy demonstrator.

Interactive multimedia

The use of interactive multimedia programmes for revision of anatomy has been shown to positively affect examination scores.³⁰ It has been suggested that visual aids should be considered compulsory for anatomy teaching, and that virtual dissection should be offered to all students.²³ The VR temporal bone simulator presents clinically oriented anatomy education in an interactive model that students can access via either a worksheet outlining a step-by-step dissection or through self-guided exploration. The simulator could be rotated in 3D virtual space and a 'fresh' temporal bone could be generated after virtual dissection, with or without the highlighting of the anatomy.

Procedural and clinical anatomy

Integrating the clinical relevance of anatomy into education has resulted in effective and engaging anatomy courses that are well received by medical students.¹⁴ It is, therefore, understandable that there has been a push toward clinically relevant anatomy education in modern medical curricula.¹⁷ This VR training module integrated clinically relevant information into the audio presented, and defined specific anatomic structures as surgically relevant. A worksheet was given which allowed students to follow a surgical-style approach to the middle ear (online supplemental appendix II). For example, the participant was directed to drill away the mastoid bone and proceed to explore the relation of the facial nerve within the mastoid bone prior to exposing the middle ear.

Study design

This randomised control trial follows an initial pilot study.³¹ In the pilot study, participants were randomised to the aforementioned

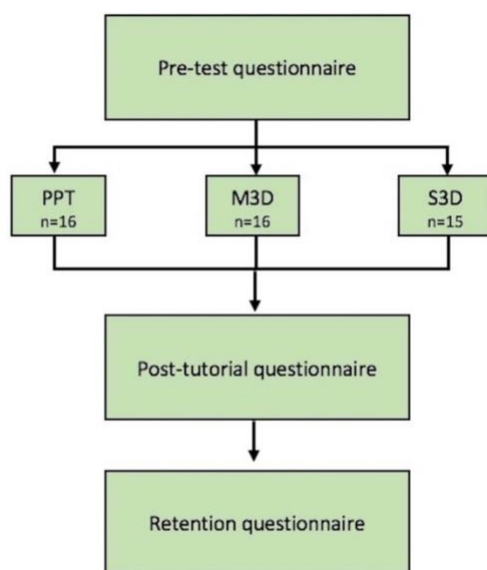


Figure 3 Overview of the methods. M3D, monoscopic 3D group; PPT, presented the same content; S3D, stereoscopic 3D group.

stereoscopic VR teaching module (S3D) or to a 2D, non-interactive version which presented the same content (PPT). The 2D version was developed by generating screenshots of the simulator at each step of the worksheet. These were displayed on a Microsoft Powerpoint presentation (V.16.18), with relevant audio accompaniment. In the current study, to further evaluate the effects of differing display technologies, participants were block randomised using Qualtrics software (Provo, UT) into one of three groups. Two of the groups were the same as that of the pilot study: S3D and PPT. The third group was allocated to the monoscopic 3D display (M3D), where the participants did not use the NVIDIA 3D glasses and thus had no depth perception. In this mode, the temporal bone appeared in 3D on a computer screen and the haptic device was still used for interaction.

An initial pretutorial questionnaire was completed by all participants (figure 3). The questionnaire comprised demographic questions, followed by questions related to the participants' self-assessed ability in temporal bone anatomy and clinical otolaryngology based on a five-point Likert scale. Lastly, the

questionnaire included 13 quiz questions regarding temporal bone anatomy (including spatial relationships and clinically orientated anatomy) (online supplemental appendix III). The participants then proceeded to the training module. All participants were given orientation to the lie of the temporal bone (eg, anterior/posterior borders). The S3D and M3D groups were orientated to the use of the haptic device and virtual environment with a 5 min explanation of the components of the simulator followed by 5 min' practice time on a simulated temporal bone. All participants were given a transcript of the embedded audio and allowed to make notes. After proceeding through the worksheet/PPT presentation, the module was reset, and the participants were allowed to redo it in part or in full. A time limit of 2 hours was set, and no additional feedback, prompting or debriefing was given during or after the module. Directly after the training module was completed, participants completed a post-tutorial questionnaire. This included five-point Likert scale type questions similar to the initial survey, as well as 10 temporal bone anatomy quiz questions (including spatial relationships and clinically orientated anatomy) (online supplemental appendix III). As there are no validated temporal bone anatomical questionnaires, the initial and postmodule anatomy questions were derived from analysis of those included the pilot study. The 50 pilot questions were analysed for discrimination and difficulty indices. Question items with Difficulty Indices of 0.4–0.6 (acceptable)^{32,33} and Discrimination Indices of 0.4–0.6 (good-excellent discrimination)^{32,33} were included. The pretutorial and post-tutorial temporal bone anatomy quiz questions were similar in theme but different in content. All participants were emailed a retention survey at 6 weeks after training which included a repeat of all 23 anatomy questions previously presented. All quiz questionnaires were distributed using Qualtrics software, with the participant's name blinded to the reviewer while analysing results. The participants were recruited and followed up between October 2018 and April 2019.

Statistical analysis

Stata/SE V.13.0 was used for all analyses.³⁴ Baseline demographic characteristics were analysed using one-way analysis of variance (age, medical school year, mastoid experience, VR experience, and gaming experience) and χ^2 test (gender and handedness) (table 1). The baseline five-point Likert scale questionnaire was analysed using χ^2 tests after the answers were condensed (agree and strongly agree allocated to a single category of response) (table 2). The Likert type questions in the post-tutorial questionnaire were similarly condensed and analysed using χ^2 tests. The group as a whole was compared with their pretutorial Likert questionnaire answers using paired t-tests, with effect sizes analysed

Table 1 Baseline participant characteristics

Baseline characteristics		PPT	M3D	S3D	P value
Age	Mean (SD)	22.69 (2.36)	23.94 (4.77)	22.4 (0.99)	0.36
Gender	Female n (%)	9 (56.25)	7 (43.75)	6 (40)	0.63
MD year	Mean (SD)	1.63 (0.72)	1.63 (.5)	1.53 (0.64)	0.9
Mastoid experience (no)	Mean (SD)	0 (0)	0 (0)	0 (0)	
VR experience (no)	Mean (SD)	0 (0)	0.06 (0.25)	0 (0)	0.39
Gaming experience (subjective)	Mean (SD)	1.75 (0.86)	1.5 (0.63)	1.67 (0.61)	0.6
Handed	Right n (%)	15 (93.75)	14 (87.5)	15 (100)	0.36

Age, medical student year (MD year); previous mastoid experience (previous observation of mastoid surgery); previous VR experience (previous use of a VR temporal bone simulator); gaming experience (subjective experience; none, casual, skilled or extreme); handedness. Mean and SDs given with one-way ANOVA p value for age, MD year, mastoid experience, VR experience and gaming experience. Number of respondents and percentage given with χ^2 values for gender and handedness.

ANOVA, analysis of variance; M3D, monoscopic 3D group; PPT, 2D group; S3D, stereoscopic 3D group; VR, virtual reality.

Original research

Table 2 Baseline education experience

Baseline educational experience	Agree or strongly agree N (%)			P value
	PPT	M3D	S3D	
I feel confident in my knowledge of the temporal bone and inner ear anatomy	1 (6.25)	1 (6.25)	4 (26.67)	0.15
I understand the temporal bone and inner ear as a 3D structure	5 (31.25)	8 (50)	7 (46.67)	0.52
I prefer to learn anatomy alone	3 (31.25)	10 (62.5)	8 (53.33)	0.192
I prefer to learn anatomy in a group	7 (43.75)	2 (12.5)	8 (53.33)	0.045
I find textbook revision an effective way to learn temporal bone and inner ear anatomy	8 (50)	7 (43.75)	5 (33.33)	0.64
I find didactic lectures an effective way to learn temporal bone and inner ear anatomy	8 (50)	4 (25)	6 (40)	0.34
I feel prepared for an ENT rotation	2 (12.5)	0 (0)	1 (6.67)	0.35
I understand the possible complications of ear surgery	3 (31.25)	3 (31.25)	1 (6.67)	0.55
I feel prepared to perform an ear examination in ED or GP	3 (31.25)	2 (12.5)	2 (13.33)	0.87
I am interested in a career in ENT	6 (37.5)	6 (37.5)	4 (26.67)	0.77

P values of χ^2 test.

Number and percentage of participants who responded agree or strongly agree to the given statements.

P value significance <0.05 (bold).

3D, three dimensional; ENT, ear, nose and throat; GP, general practitioner; M3D, monoscopic 3D group; PPT, presented the same content; S3D, stereoscopic 3D group.

using Cohen's d. A Cohen's d result of 0.2 was considered a small effect size, 0.5 medium and 0.8 large.³⁵ The total scores in the post-tutorial and retention tests were compared with the pretutorial scores using paired t tests and effect sizes were analysed using Cohen's d (table 3). The post-tutorial questionnaire results were analysed by group, comparing pretutorial scores to an adjusted post-tutorial test score with analysis of covariance (ANCOVA) regression. Similarly, the adjusted results of the retention test questionnaire were analysed by group, comparing to pretutorial scores with ANCOVA regression (table 4). Sub analyses were performed with pairwise comparisons.

RESULTS

Participant demographics

A total of 47 medical students from the University of Melbourne postgraduate medical programme completed the training module, as well as the pretutorial and post-tutorial questionnaire. There were 16 participants in the PPT group, 16 participants in the M3D group and 15 participants in the S3D group. The retention questionnaire was completed by 23 participants (48.9%). There were 22 female participants and 25 male participants, of which 22 were in their first year and 25 in their second year. The mean age of participants was 23.0 years. No participants had previously observed mastoid surgery and one student had previously used a VR simulator. The mean subjective gaming experience was 1.64, which falls between casual and skilled on the four-point scale presented (none, casual, skilled, extreme). There were three left-handed participants. There was no significant difference between groups in any of these baseline characteristics (table 1). Students' attitudes to their style of learning, anatomy knowledge and preparedness for clinical practice in ear, nose and throat (ENT) were explored (table 2). Prior to participating in the teaching module, the students exhibited low confidence in their knowledge of temporal bone anatomy and were not confident in their preparedness for a clinical rotation in ENT, with no significant difference between groups. The M3D group were significantly less comfortable learning anatomy in a group setting ($p=0.045$).

Subjective experience of the training module

Compared with their pretutorial experience, students in all groups felt significantly more confident with temporal bone and inner ear anatomy after completing their respective module. Scores reported by those in the S3D group suggested they felt a greater subjective understanding of the anatomy as a 3D

structure ($p=0.031$) (table 3). As a whole group, students felt more comfortable with their preparedness to use the anatomical knowledge in a clinical context, including clinical examination and understanding how pathology arises. Both the M3D and S3D groups felt that the training module was effective and supported future exposure to this style of learning (figure 4). The S3D learning platform showed a significant benefit in ease of use.

Quantitative questionnaire results

As a whole group, the participants showed significant improvements in test scores with a medium to large effect size ($p\leq 0.005$) (table 3). The 23 participants who returned the retention questionnaire exhibited a significant improvement in total scores (retention score $M=50.09$, $SD=6.45$, pretutorial score $M=35.28$, $SD=19.04$) and clinical and spatial relations scores (retention score $M=43.12$, $SD=20.20$, pretutorial score $M=21.12$, $SD=8.89$) with large effect sizes (total score Cohen's $d=0.83$, clinical and spatial relations score Cohen's $d=1.24$). There was no significant improvement in retention of participants' identification of anatomic structures scores across the whole group (retention score $M=57.71$, $SD=21.73$, pretutorial score $M=51.81$, $SD=30.25$) (table 3).

When analysed by group (table 4, figure 5), there were no significant differences between groups with respect to post-tutorial or retention questionnaire 'total' and 'anatomy' scores. Pairwise comparisons between groups revealed a significant difference between the adjusted post-tutorial questionnaire 'total' scores of the M3D and S3D groups ($p=0.048$; S3D 64.63, 95% CI 57.21 to 73.07 compared with M3D 53.79%, 95% CI 46.45 to 61.73). There was also a significant difference in the results of the post-tutorial questionnaire scores for the clinical and spatial relation domain between the PPT and S3D ($p=0.010$, S3D 66.50%, 95% CI 56.46 to 76.54, PPT 47.76%, 95% CI 38.00 to 57.51). Neither of these differences were seen in the retention subgroup analyses. For total questions and anatomy domains, the pretutorial scores had a significant effect on the post-tutorial scores and retention scores (total post-tutorial $p=0.005$, total retention $p=0.003$, anatomy post-tutorial $p=0.030$, anatomy retention $p=0.005$). There was no significant effect of the pretutorial results on the post-tutorial or retention scores for the clinical and spatial relations domains.

DISCUSSION

This study presents an effective training module in clinically oriented temporal bone anatomy, which facilitates significant acquisition of knowledge. These results are consistent with those

Table 3 Summary of post-tutorial questionnaire results and comparison to pretutorial results

Post-tutorial questionnaire	Agree or strongly agree N (%)				Whole group comparison to pre-tutorial (paired t-test)				Cohen's d
	PPT	M3D	53D	P value	M pre (SD)	M post (SD)	t	P value	
Confident knowledge PTB anat	8 (50)	7 (43.75)	11 (73.33)	0.221	0.13 (0.34)	0.55 (0.5)	5.39	<0.005	0.99
Understand 3D PTB	8 (50)	11 (68.75)	14 (93.33)	0.031	0.43 (0.50)	0.70 (0.46)	3.51	0.001	0.57
Prefer module alone	4 (25)	8 (50)	7 (46.67)	0.296					
Prefer module group	8 (50)	8 (50)	10 (66.67)	0.563					
Textbooks effective	8 (50)	5 (31.25)	8 (53.33)	0.406	0.43 (0.50)	0.45 (0.50)	0.33	0.743	0.04
Lectures effective	8 (50)	4 (25)	7 (46.67)	0.296	0.38 (0.49)	0.40 (0.50)	0.33	0.743	0.04
Prepared ENT rotation	4 (25)	4 (25)	5 (33.33)	0.838	0.06 (0.25)	0.28 (0.45)	2.87	0.006	0.58
Understand complications	14 (87.5)	10 (62.5)	11 (73.33)	0.267	0.15 (0.36)	0.74 (0.44)	8.23	<0.005	1.48
Prepared for ENT examination	5 (31.25)	5 (31.25)	6 (40)	0.840	0.15 (0.36)	0.34 (0.48)	2.87	0.006	0.45
Career interest ENT	7 (43.75)	12 (75)	4 (26.67)	0.024	0.34 (0.48)	0.49 (0.50)	2.45	0.017	0.30
Module easy	4 (25)	7 (43.75)	13 (86.67)	0.024					
Module effective	4 (25)	11 (68.75)	12 (75)	0.004					
Would use again	4 (25)	14 (87.5)	13 (86.67)	<0.005	33.44 (17.91)	58.09 (17.12)	0.09	<0.005	1.41
Total score									
Anatomy score					45.50 (28.88)	60.00 (20.11)	3.65	<0.005	0.58
Clinical and relations score					23.10 (4.76)	56.17 (20.28)	9.58	<0.005	1.86
Comparison to retention n=23					M pre (SD)	M ret (SD)			
Total score					35.28 (19.04)	50.09 (6.48)	4.96	<0.005	0.83
Anatomy score					51.81 (30.25)	57.71 (21.73)	1.08	0.292	0.22
Clinical and relations score					12.11 (8.89)	43.12 (20.20)	5.58	<0.005	1.24

Number and percentage of participants who responded agree or strongly agree to the given statements. Whole group means and standard deviations for both post-tutorial questionnaire and retention questionnaire are presented in the same content; PTB, petrous temporal bone; PPT, petrous temporal bone; M3D, monoscopic 3D group; PPT, petrous temporal bone; 53D, stereoscopic 3D group.

P value significance <0.05 (bold)

Number and percentage of participants who responded agree or strongly agree to the given statements. Whole group means and standard deviations for both post-tutorial questionnaire and retention questionnaire are presented in the same content; PTB, petrous temporal bone; PPT, petrous temporal bone; M3D, monoscopic 3D group; PPT, petrous temporal bone; 53D, stereoscopic 3D group.

Original research

Table 4 Summary of questionnaire results by group

	Mean pretest (%)	95% CI	P value	Adj post-test (%)	95% CI	P value	Adj ret test (%)	95% CI	P value
Total			0.238			0.103			0.937
PPT	27.31	18.50 to 36.11		61.87	47.69 to 63.25		51.08	41.41 to 60.75	
M3D	35.82	27.03 to 44.61		53.79	46.45 to 61.73		48.9	39.89 to 57.90	
S3D	37.44	27.96 to 46.92		64.63	57.21 to 73.07		50.58	39.45 to 61.71	
Anat			0.210			0.235			0.209
PPT	35.21	20.42 to 50.00		61.87	52.49 to 71.25		67.37	53.82 to 80.92	
M3D	49.48	35.91 to 63.04		53.79	44.59 to 63.00		52.38	39.67 to 65.10	
S3D	52.22	37.09 to 67.36		64.63	55.07 to 74.18		52.81	37.09 to 68.52	
Clin/relat			0.697			0.034			0.303
PPT	20.54	12.67 to 28.40		47.76	38.00 to 57.51		34.87	21.10 to 48.64	
M3D	24.11	17.30 to 30.91		54.90	45.19 to 64.61		45.95	33.06 to 58.64	
S3D	24.76	16.60 to 32.93		66.50	56.46 to 76.54		50.01	34.38 to 65.64	

Mean pretest (pretest) scores with 95% CIs. ANCOVA regression analysis with adjusted post-tutorial (post-test) and adjusted retention test (ret test) means with 95% CIs. Comparison between groups with χ^2 test, p values given.

ANCOVA, analysis of covariance; M3D, monoscopic 3D group; PPT, presented the same content; S3D, stereoscopic 3D group.

identified in the pilot study.³¹ In addition, as a group there was adequate retention of overall knowledge (as evidenced by 'total' score outcomes). This was mainly due to the retention of clinically oriented information and the spatial relationships between anatomical structures.

The display technology applied did not bear significant effect in the majority of knowledge outcomes, except that 3D technologies exhibited significant benefit in facilitating learning of clinically oriented and structural relational outcomes. Although the training of spatial relationships has not been assessed in previous temporal bone anatomy modules, Estevez *et al* demonstrated the benefit of 3D physical modelling in teaching spatial relationships in similarly complex neuroanatomy.³⁶ While the importance of clinically oriented anatomy modules has been established,³⁷ this study suggests a particular benefit to the 3D display technology in imparting clinically oriented anatomy knowledge. Hariri *et al* previously explored the benefit of VR simulation in teaching clinical anatomy of the shoulder joint, and although results were not inferior to the comparison textbook group, the participants in the simulation group exhibited greater motivation for learning in the VR environment.³⁸ Further to this, Jurgaitis *et al* reported the superiority of 3D hepatic visualisations in students' ability to understand liver segmental anatomy, as well as the clinical tasks of identifying liver resection margins and predict possible intraoperative difficulties related to hepatic anatomy.³⁹ Similar to the learning of clinically oriented temporal bone anatomy, these tasks required the understanding of complex 3D anatomy and spatial relationships. This is likely explained by the benefit of 3D display technologies to train anatomy with reduced cognitive load required by participants, as has been previously demonstrated.^{40–42} In addition, both the 3D displays were subjectively more effective than the 2D display and the participants were significantly more likely to report they would use these modules again. In a meta-analysis of 2226 participants in 2015, Yammine and Violato suggested the superiority of user satisfaction and perceived effectiveness of 3D visualisation technologies may

reflect the novelty of the method.⁸ However, in this study, a significantly higher percentage of students also found the S3D module easier to use than the other displays. This correlates to the findings of Huang *et al* that immersion features of stereoscopic 3D VR anatomy courses positively impact perceived usefulness and ease of use.⁴³ The unique benefits of stereoscopic 3D displays have been explored by McIntire *et al* in a comprehensive literature review, concluding that S3D is of particular benefit in complex tasks for novice learners and in tasks requiring spatial manipulations of objects, spatial understanding, memory and recall.⁴⁴

Turney suggests that in modern medical curricula, the innate fascination with anatomy should be encouraged and that anatomy courses should promote student interest through clinical relevance and technology.¹⁷ To ensure medical practitioners have sufficient anatomy knowledge to practise safely, and to aid in retention of this knowledge, Turney suggested that anatomy education be delivered in a vertical approach, where the student initially learns core anatomy, revisiting the topics in a more clinically relevant, specialised approach later on in medical school and junior doctor years. The clinically oriented VR temporal bone anatomy module studied here lends itself to this style of vertical learning, and would be an appropriate module to bridge the gap between core anatomy knowledge of basic sciences and specialty-specific anatomy training.¹⁴ In addition, while Morgan *et al* noted the high labour associated with development and implementation of specialty-specific anatomy courses, this study exhibits a self-directed module that facilitated improvement in anatomy knowledge despite the absence of anatomy demonstrators. With regards to the benefits of differing display modalities, it was observed that there was a significant benefit of S3D over M3D in immediate overall knowledge gain, and S3D over PPT in immediate knowledge gain and understanding clinical and spatial relationships. This benefit did not extend to retention of the naming of individual anatomical structures which may reflect



Figure 4 Results of the Likert scale for subjective experience. Percentage of respondents who agreed or strongly agreed with the statements 'I found this module easy to use', 'I would use this way of learning again', 'I found this an effective way to learn temporal bone and inner ear anatomy'. M3D, monoscopic 3D group; PPT, presented the same content; S3D, stereoscopic 3D group.



Figure 5 Mean pretest results, with CIs. Adjusted means post tutorial, linear regression analysis accounting for pretest scores, with CIs. Adjusted means retention score of the 23 respondents, linear regression analysis accounting for the pretest scores of these 23 respondents. M3D, monoscopic 3D group; PPT, presented the same content; S3D, stereoscopic 3D group.

Original research

What is already known on this subject

- ▶ Three-dimensional (3D) technologies and clinically oriented content are important adjuncts to time-limited anatomy teaching.
- ▶ A limited evidence base suggests that 3D technologies are promising in training inner ear and temporal bone anatomy.

What this study adds

- ▶ A clinically orientated, procedural, and interactive virtual reality temporal bone anatomy module was developed and found to be efficient in facilitating knowledge acquisition of medical students.
- ▶ Of the three display technologies compared (two-dimensional (2D), monoscopic 3D, and stereoscopic 3D), there was no benefit in the majority of learning outcomes.
- ▶ 3D display exhibited a marginal benefit for clinically oriented and structural relation outcomes, as well as ease of use, perceived effectiveness, and students' preference to use again.

the under-representation of participant responses or could be an indication that this aspect of anatomy was not as important to the learners. The latter interpretation is supports the conclusions drawn from a review of medical curricula, where it was argued that greater importance should be placed on the participant's subjective experience, in which both the M3D and S3D modules were evidently superior.¹⁷

It was observed that this clinically oriented module also improved students' subjective confidence in their knowledge of anatomy as well as their interest in and preparedness for clinical work relating to otolaryngology. These alternative learning outcomes have previously been identified as benefits of anatomy education through cadaveric dissection.⁴⁵ Given that the face validity of our simulator has previously been demonstrated,⁴⁶ it is expected that these additional learning outcomes associated with cadaveric dissection courses would also be seen in VR simulation training. This is particularly important for otolaryngology education, as it has been identified that medical school graduates have poor comfort levels in otolaryngology despite this discipline forming an essential component of primary healthcare.⁴⁷

The findings of this study suggest that 3D technologies should continue to be integrated in anatomy education and can be successfully used to present clinically relevant content. Furthermore, this content can be delivered in a self-directed platform, facilitating reallocation of valuable anatomy demonstrator resources to more advanced and complex anatomic discussions.

There were several limitations identified in this study. First, given there is no standardised Australian anatomy curriculum,⁴ the information given in this module relied on expert opinion as to what was sufficient and appropriate. In addition, due to the absence of previously validated assessment tools for temporal bone anatomy education, the assessment questions were those evaluated as appropriately difficult and effective discriminators in the pilot study. To allow assessment of understanding, different questions were asked in the pretutorial and post-tutorial questionnaires. The themes of these questions were similar, although in particular for the clinical questions, the content was varied, particularly for the clinical material. The retention test was completed by under half of the participants, introducing a

bias of respondents, thus limiting the assessment of retention of knowledge.

CONCLUSION

The VR temporal bone anatomy tutor was developed along the guidelines for an optimal anatomy curriculum. Notwithstanding the above limitations, it is an effective self-guided clinically oriented anatomy tutor in both 3D and 2D visual displays for imparting factual knowledge. The 3D display technologies had greater user satisfaction and were more effective in training clinically oriented anatomy and spatial relationships. Stereoscopic 3D exhibited particular benefit in ease of use. With the flexibility to incorporate varying levels of detail and a standardised curriculum, this module lends itself to a range of applications from undergraduate medical education to specialty specific anatomy education.

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Figure 4 enlarged:

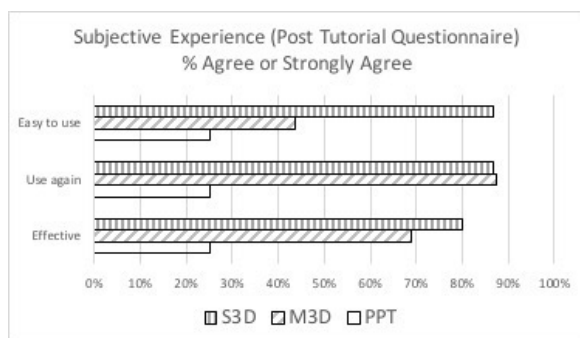
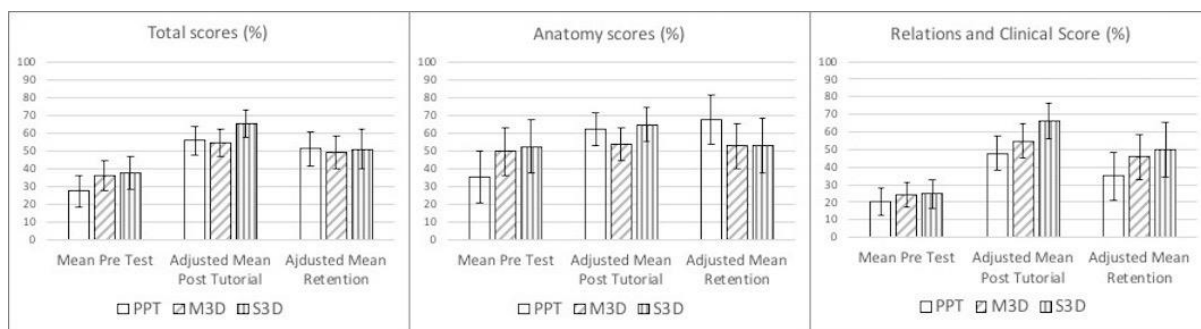


Figure 5 enlarged:



Chapter 3: Virtual reality simulation in advanced temporal bone procedural training

Introduction

The prevalence of cochlear implantations has been predicted to increase, both due to an ageing population and widened criteria for eligibility (17). Concurrently, surgical training is exposed to similar resource pressures as anatomy education (1, 2, 119). The positive results of using virtual reality simulators in mastoidectomy training are encouraging and raise to question whether this environment may also foster education in the more advanced temporal bone procedures such as preparation for cochlear implantation. Virtual reality simulators have had promising results in training other advanced surgical procedures such as advanced bariatric surgery (222) and brain tumour resections of neurosurgery (223). However, to the author's knowledge, there have been no studies evaluating virtual reality simulation for advanced temporal bone surgery.

An objective assessment tool is required for reliably assessing the benefit of surgical training interventions (202). There have been multiple assessment tools developed for objectively assessing mastoidectomy surgery (205, 224, 225) and these have been used in assessing the benefit of virtual reality simulation modules for mastoidectomy surgery (152, 165). Piromchai et al. developed and validated an objective assessment tool for cochlear implant surgery (52). The development of this tool has provided the foundation for developing an advanced temporal bone surgery module.

The objective of this chapter was to develop and assess a virtual reality simulation module in the training of the advanced temporal bone surgery required for cochlear implantation.

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Supporting skill acquisition in cochlear implant surgery through virtual reality simulation

Bridget Copson ¹, **Sudanthi Wijewickrema**¹, **Yun Zhou**¹, **Patorn Piromchai**^{1,2}, **Robert Briggs**¹, **James Bailey**³, **Gregor Kennedy**⁴, **Stephen O'Leary**¹

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Objectives: To evaluate the effectiveness of a virtual reality (VR) temporal bone simulator in training cochlear implant surgery.

Methods: We compared the performance of 12 otolaryngology registrars conducting simulated cochlear implant surgery before (pre-test) and after (post-tests) receiving training on a VR temporal bone surgery simulator with automated performance feedback. The post-test tasks were two temporal bones, one that was a mirror image of the temporal bone used as a pre-test and the other, a novel temporal bone. Participant performances were assessed by an otologist with a validated cochlear implant competency assessment tool. Structural damage was derived from an automatically generated simulator metric and compared between time points.

Results: Wilcoxon signed-rank test showed that there was a significant improvement with a large effect size in the total performance scores between the pre-test (PT) and both the first and second post-tests (PT1, PT2) (PT-PT1: $P = 0.007$, $r = 0.78$, PT-PT2: $P = 0.005$, $r = 0.82$).

Conclusion: The results of the study indicate that VR simulation with automated guidance can effectively be used to train surgeons in training complex temporal bone surgeries such as cochlear implantation.

Keywords: Virtual reality, ENT, Simulation, Surgery, Training, Cochlear implant, Cochleostomy, Skill acquisition

Introduction

The key to cochlear implantation is that the electrode should pass along an optimal insertion vector, which is coaxial to the centreline of the lower-basal turn of the scala tympani. This vector may be approached surgically by a cochleostomy or the round window (Briggs *et al.*, 2005; Meshik *et al.*, 2010). Either approach requires good visualization of the round window and removal of its bony overhang, as the latter increases the visibility of the round window membrane by up to 3-fold (Roland *et al.*, 2007; Shapira *et al.*, 2011). It has been demonstrated that the optimal insertion vector of a cochlear implant electrode passes in very close proximity to the facial nerve (Meshik *et al.*, 2010). Therefore, cochlear implant surgery requires thorough skeletonization of the facial nerve and

chorda tympani in the facial recess and visualization of the round window.

The traditional approach to surgical training in otology has been apprenticeship in the operating theatre and temporal bone dissection (Arora *et al.*, 2012; Duckworth *et al.*, 2008; George & De, 2010). With decreasing availability of cadaveric temporal bones worldwide, time pressure on expert trainers (Piromchai *et al.*, 2014) and financial pressure on the health system (Wiet *et al.*, 2011) there has been a move towards alternative training tools (Wiet *et al.*, 2009). Simulation training is an attractive option as it provides the learner a cost effective, risk free environment for repetitive practice with the ability to objectively assess technical skills and provide feedback, which promotes self-directed learning (Blevins & Girod, 2006; Hatala *et al.*, 2014; Laeq *et al.*, 2009; Wiet *et al.*, 2011; Zhao *et al.*, 2011a, 2011b; Zirkle *et al.*, 2007).

Virtual reality (VR) simulation trainers facilitates skills acquisition and transfer of these to the operating

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room, as evidenced by improved overall performance, shorter procedural time and fewer surgical errors in surgical trainees who receive VR simulation (Dawe *et al.*, 2014). Although the effectiveness of VR simulation for mastoidectomy training has been well established (Arora *et al.*, 2014; Francis *et al.*, 2012; Khemani *et al.*, 2012; Sewell *et al.*, 2008; Wiet *et al.*, 2012; Zhao *et al.*, 2010, Zhao *et al.*, 2011a, 2011b), to the authors' knowledge there have been no studies evaluating the use of VR simulation for more complex temporal bone procedures such as a posterior tympanotomy in preparation for cochlear implantation. In addition, with the ongoing advances in electrode design, a simulation platform where surgeons could practice the preparation of the temporal bone for specific electrodes (for example the straight sheath of the Modiolar Research Array by Cochlear Corporation (Sydney Australia)) may be invaluable (Briggs *et al.*, 2011). The aim of this study was to bridge this gap by investigating whether a specific VR training module could improve dissection of the temporal bone in preparation for cochlear implantation.

Materials and methods

Setting

The University of Melbourne VR temporal bone surgery simulator was used in this study. Face and content validity of this simulator has previously been validated (Zhao *et al.*, 2010, Zhao *et al.*, 2011a, 2011b). The virtual temporal bones were derived from microcomputed tomography of cadaveric temporal bones (Zhao *et al.*, Zhao *et al.*, 2011a, 2011b), from which anatomical structures had been segmented manually, rendered in 3D and visualized on a 3D computer monitor. The surgical drill was implemented on a commercially available 3D pointing device that provided force-feedback (Sensable Phantom Omni) and drill adjustments were implemented using a midi attachment. Using the University of Melbourne VR temporal bone surgery simulator, a surgeon can perform middle and inner ear operations. Figure 1

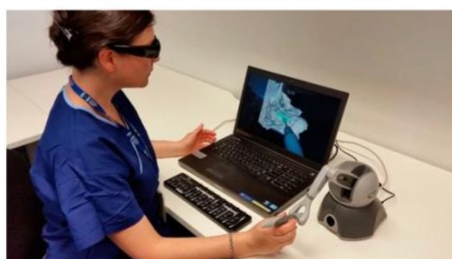


Figure 1 A surgeon using the University of Melbourne VR temporal bone surgery simulator to perform cochlear implant surgery.

shows a surgeon performing a cochlear implant surgery using this simulator.

The teaching curriculum was based upon an expert training dataset, obtained by recording the simulation as a consultant otological surgeon performed a posterior tympanotomy in preparation for cochlear implantation (including skeletization of the facial nerve and chorda tympani to optimize the facial recess, preparation of the round window niche and drilling of the antero-inferior cochleostomy). The simulated surgery was then divided into a sequential series of surgical steps that a trainee was expected to follow.

Real-time guidance was provided to trainees during the simulation. The bone (voxels) to be removed during each step of the procedure was determined from the expert training dataset. At each stage of the procedure, the next bone to be removed was identified by a visual cue – namely a change in the colour of the bone – so as to guide its' step-wise removal within the surgical context. A suggestion on burr size and type was also displayed visually according to those used at each step of the procedure by the otological surgeon. This step-by-step guidance was delivered during training in an 'instruction' module. The bone-removal guidance was associated with pre-recorded verbal advice pertaining to the anatomical landmarks and surgical technique appropriate for that step of the procedure, and the surgical significance of removal of

Table 1 Verbal advice provided in the temporal bone simulation

Drill along the line of facial nerve using the incus short process and lateral semi-circular canals as landmarks until the descending facial nerve is identified
Once you reach the level of the facial nerve or chorda tympani, change to a smaller burr and increase magnification
Carefully define the buttress and the course of the facial nerve and chorda tympani
Reduce burr size and drill through the facial recess adjacent to the mid-point of the buttress level with tip of incus short process
Adjust rotation inferiorly and increase magnification for better view of the facial recess and round window niche
Change to a smaller burr and skeletonize the facial nerve and chorda tympani at their junction to widen the facial recess
Increase burr size to drill anterior to facial nerve, lateral aspect of the sinus tympani
Rotate to view the round window niche, change magnification, change to smaller burr and drill lip off the niche to expose true round window membrane
If the round window niche is not seen clearly, use a smaller burr to continue drilling the facial recess or use a larger burr to take more bone off the ear canal wall to improve visualization of the round window through the facial recess
Reduce burr size to perform cochleostomy. Typically a 0.8–1 mm diamond burr on a tapered shaft is preferred.
Rotate the bone to view in the direction of the basal turn.
Skeletonize the inferior border of the round window membrane, saucerize the adjacent bone, and drill a cochleostomy into the scala tympani
You have successfully completed the procedure. You can now place the electrode

the bone. For each temporal bone, the advice was tailored to specific anatomical variations. Table 1 provides an overview of the style of advice provided. After completion of the instruction, a 'practice' module then gave the surgeon the opportunity to rehearse the procedure without guidance. Summative (or terminal) feedback was then provided on how a surgeon's bone removal compared with the regions that should have been dissected (as assessed by the expert dataset). The terminal feedback was given as a percentage of the area drilled by the otology expert in both written and visual forms.

Participants

These were 12 resident surgeons ('registrars') in the nationally accredited Surgical Education and Training Program (Royal Australasian College of Surgeons) in Otolaryngology Head and Neck Surgery within Australia.

Experimental procedure

The registrars were oriented to the VR temporal bone simulator with a standard instruction video and then

given time to familiarize themselves with the haptic device and virtual environment. They were then given a VR temporal bone that had been partially dissected, with completion of the cortical mastoidectomy down to exposure of the incus. To obtain a baseline level of surgical competence, the registrars were asked to prepare the temporal bone for cochlear implantation. There was no instruction given on the steps of the procedure to the registrars at this point. This dissection served as the participant's baseline or 'pre-test' (PT). The participants were then given three different VR temporal bones, each with both the instruction and the practice modules. These modules were performed twice over the course of two sessions (the second repetition being the contralateral [or mirror image of that particular] VR temporal bone). The two sessions of teaching modules were run within the space of 5–9 days. At the end of the second session, after completing the teaching module, the registrars were given two VR temporal bones, the first a mirror image of their pre-test VR temporal bone (PT1) and the second a VR temporal bone that had not been used in the teaching scenarios (PT2). Figure 2 illustrates the design of this study.

During each procedure, the data stream was recorded together with video, using the simulator and Open Broadcast (version 063.7b) capture software respectively. 36 assessment videos were recorded in total (12 baseline assessments and 24 final assessments). The videos were deidentified and reviewed in a random sequence by one of the consultant otolaryngologist authors. Each performance was assessed using a validated tool for cochlear implant competency (Piromchai *et al.*, 2014). This tool's global competency scale was adapted from the objective structures assessment of technical skills (OSATS) (Butler & Wiet, 2007; Martin *et al.*, 1997; Zhao *et al.*, 2011a, 2011b) and the task-based checklist of surgical steps was synthesized from expert consensus and a standard otology textbook (Flint *et al.*, 2010). The structural damage was extracted from the data stream recorded by the simulator.

Ethical approval

Ethical approval was granted by the Royal Victorian Eye and Ear Hospital Ethics Committee (HREC number 15-1230H).

Statistical analysis

Non-parametric statistical analysis was conducted on SPSS (version 20.0). The Wilcoxon signed-rank test was used to compare the scores of the participants at the time intervals before and after the teaching modules and the effect sizes for these comparisons were subsequently calculated ($r = z/\text{square root of } N$). A small effect is represented by an r score of 0.1,

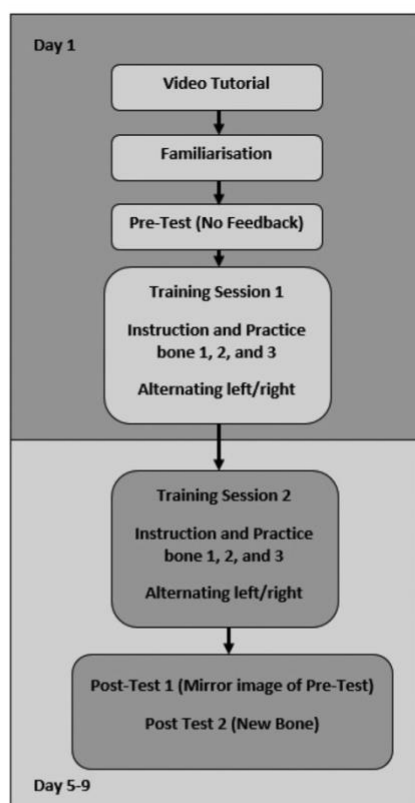


Figure 2 Flow diagram of study design.

medium effect $r = 0.3$ and large effect $r = 0.5$ (Cohen, 1988). The median scores were calculated with interquartile ranges.

Results

Participant demographics

The mean age of participants was 34.4 years, the female to male ratio was 1:3, and the left to right handed ratio was 1:2. Most participants had undergone 3–4 years of the 5-year Surgical Education and Training program (average 3.25, standard deviation 1.35). Participants had been involved in mastoid surgery a median of 20 times (interquartile range (IQR) 10) as the assistant and a median of 16.5 (IQR 29.5) times as the surgeon. An average of 3.08 temporal bone courses had been attended per participant with an average of 11.17 temporal bones having been drilled. Only three participants had previously drilled VR temporal bones. Of the options for gaming experience (none, casual, skilled and extreme), the average gaming experience was casual.

Global rating scale for cochlear implant competency

The boxplots in Figures 3 and 4 give the median and interquartile range values for the global rating items and total score. There was a significant improvement (with a large effect size) found in the total score of the global rating scale between the baseline assessment (PT) and both post training assessments (PT1, PT2) (PT to PT1 $P = 0.026$, $r = 0.643$; PT to PT2 $P = 0.003$, $r = 0.848$). When analysed by assessment item, the greatest statistically significant improvement was seen in the items 'knowledge of the specific procedure', 'flow of the operation' and 'overall surgical performance' as seen in Table 2.

Task-based checklist for cochlear implant competency

The boxplot graphs in Figures 5 and 6 give the median and interquartile range values for the task-based checklist items and total score. Similar to the global rating score, there was a significant improvement with a large effect size in the total score of the task-based checklist between the baseline assessment and the post training assessments (PT to PT1 $P = 0.008$, $r = 0.77$; PT to PT2 $P = 0.027$, $r = 0.638$). As demonstrated in Figure 5, the greatest significant improvements were seen in the steps of removing bone anterior to the fallopian canal, visualization of the round window niche through the facial recess and drilling of the cochleostomy.

Damage to anatomical structure

The boxplots in Figure 7 show the median and interquartile range values for the injury to anatomical structures. Anatomical structure damage is determined

by the voxels of an anatomical structure inadvertently drilled (inferring damage to that structure) as a percentage of the total voxels drilled in the specimen. The percentage is used so that a fair comparison between participants and across different specimens can be performed. There was a significant improvement in the structural damage with a large effect size between the baseline assessment (PT) and both post training assessments (PT1 and PT2) (PT to PT1 $P = 0.023$, $r = 0.657$; PT to PT2 $P = 0.010$, $r = 0.747$).

Discussion

The findings of this study indicate that a VR simulation training module improved the technique of Otolaryngology registrars performing cochlear implant surgery. Not only did participants show an improvement in drilling VR temporal bones that had been previously encountered, they were also able to translate these skills to a VR temporal bone that had not been seen previously. These results are consistent with previous studies using VR simulation training for cortical mastoidectomy (Arora et al., 2014; Francis et al., 2012; Khemani et al., 2012; Sewell et al., 2008; Wiet et al., 2012; Zhao et al., 2010) but to the authors' knowledge this is the first study to show a training advantage in advanced temporal bone surgery. A limitation of this study is that it did not assess the effect of simulation training on 'real life' performance in the operating theatre. Although transferability of skills has been shown in laparoscopic surgery after VR simulation (Ahlberg et al., 2007; Cosman et al., 2007), it remains unclear whether VR simulation in otolaryngology provides practical advantage in the operating theatre (Piromchai et al., 2015).

In surgical training, mastery-orientated goals (focusing on the acquisition of skills) have been shown to improve the adaptability of the participant to complete more complex tasks (Kozlowski et al., 2001). It is becoming more common for simulators to include performance goals (Dawe et al., 2014) and inclusion of these goals into a training module (termed proficiency based simulation) has shown improvement in clinical outcomes (Ahlberg et al., 2007). These performance goals are often derived from the average of expert performance (Dawe et al., 2014). In this simulator module, we provided performance goals through the provision of concurrent and terminal feedback, where an end product goal was defined as the regions of bone drilled by an expert otologist. Although previous studies have shown similarity between experts in regards to psychomotor skills (Ioannou et al., 2014) and end product assessment (Piromchai et al., 2014), it cannot be assumed that expert surgeons will perform all the steps of advanced temporal bone surgery in the same spatial and

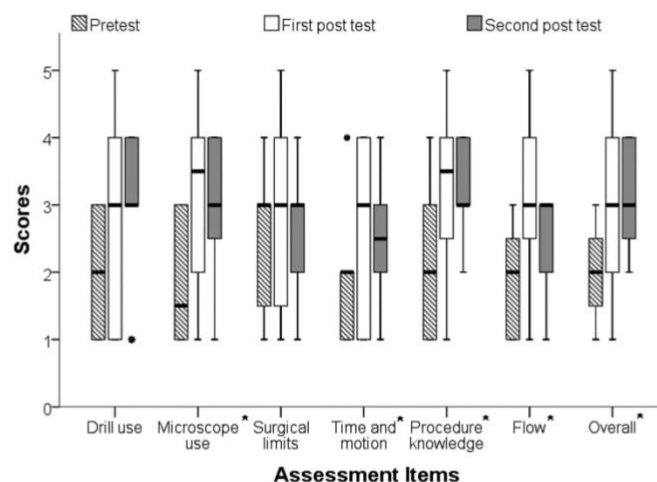


Figure 3 Global rating scale assessment items in boxplot showing median and interquartile range and 90th percentile, circle denotes outliers. Significant differences were observed in the items indicated by an asterisk.

temporal style. It was therefore appropriate in this study to base the specific surgical steps and guidance on a single expert cochlear implant surgeon's performance.

In addition, there have been differing reports of the effectiveness of concurrent and terminal feedback on improving surgical performance (Chang *et al.*, 2007; Walsh *et al.*, 2009; Xeroulis *et al.*, 2007), and a meta-analysis showed no significant difference in

either the immediate or delayed skills outcomes (Hatala *et al.*, 2014). Surprisingly, there has been little evidence of the benefit of combining both terminal and concurrent feedback. In a limited randomized control trial of eight Obstetric and Gynaecology residents, Kahol *et al.* compared terminal feedback to concurrent and terminal feedback in a laparoscopic simulator and found a statistically significant improvement in those using the combined feedback (Kahol *et al.*, 2007). Here we found that surgical mastery benefited from a combination of both.

Some studies have suggested that constant concurrent feedback may be of detriment to the retention of skills due to the development of a reliance on the feedback (Schmidt & Lee, 2011; Stefanidis *et al.*, 2012; Wierinck *et al.*, 2006). Here we successfully accounted for this by alternating instruction (that included feedback) and practice (that did not).

The global rating scale assesses preparation and process and was designed to give the assessor an indication of whether the participant was competent in their overall skills sufficient to perform cochlear implant surgery (Laeq *et al.*, 2009; Zirkle *et al.*, 2007). Of note, in this study there was no significant improvement in the use of the Otologic Drill. This may be a reflection of there being no specific feedback provided on drilling technique, or that these surgeons all had had a moderate amount of experience with temporal bone surgery. The latter assumption seems more likely as the participants were fairly advanced trainees (on average 3rd year surgical registrars with an average of 24 previous mastoid temporal bone surgeries performed by the participant prior to commencing the study).

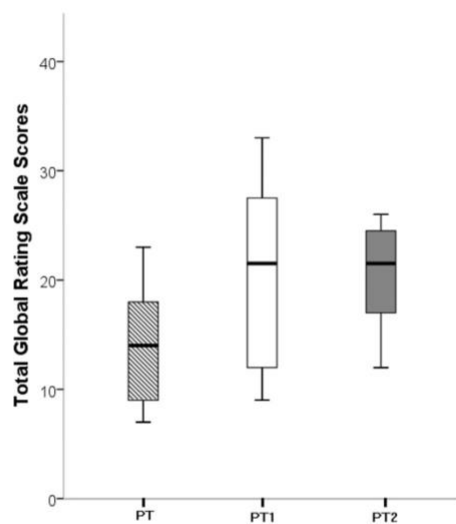


Figure 4 Total score of global rating scale assessment items in boxplot showing median and interquartile range and 90th percentile. Comparison between pre-test (PT) and both the post-tests (PT1 and PT2) were significant with large effects.

Table 2 Comparison of performance scores including *P* value and effect size (*r* value). Significant results in bold

	Pre-test to first post-test		Pre-test to second post-test		First post-test to second post-test	
	<i>P</i> value	<i>r</i> value	<i>P</i> value	<i>r</i> value	<i>P</i> value	<i>r</i> value
Total score global rating scale	0.026	0.643	0.003	0.848	0.906	0.003
Use of otologic drill	0.327	0.283	0.051	0.563	0.401	0.242
Use of microscope	0.032	0.618	0.012	0.724	0.856	0.053
Respect for surgical limits	0.272	0.317	0.559	0.169	0.720	0.104
Time and motion	0.016	0.693	0.075	0.514	0.722	0.103
Knowledge of specific procedure	0.019	0.680	0.002	0.873	0.608	0.148
Flow of operation	0.012	0.723	0.023	0.656	0.084	0.498
Overall surgical performance	0.020	0.671	0.010	0.740	0.773	0.083
Total score task-based checklist	0.008	0.780	0.027	0.638	0.223	0.352
Preserve over facial nerve	0.719	0.010	1.000	0.000	0.608	0.148
Remove bone from fallopian canal	0.007	0.783	0.010	0.740	0.414	0.235
Preserve bone over chorda tympani	0.726	0.101	0.340	0.275	0.586	0.157
Facial recess opened to visualize niche	0.009	0.759	0.039	0.596	0.037	0.601
Antero-inferior cochleostomy drill	0.018	0.681	0.102	0.471	0.074	0.516
Total combined scores of global rating scale and task-based checklist	0.007	0.782	0.005	0.816	0.694	0.113

The task-based checklist assesses the participant's ability to perform the steps of the cochlear implant procedure. Although there was an overall improvement in the total scores for the task-based checklist, and most of the separate items, there were no improvements in the scores of the preservation of bone over the facial nerve and chorda tympani. We have observed this before (Piromchai *et al.*, 2014), which raises the question

of whether this simulation platform is optimized for assessing these items. The issue may relate to the resolution of the voxels in the simulator, as there is a very fine line between skeletonizing (preserving a layer of bone over) a nerve and completely exposing it. This may provide impetus for considering higher resolution anatomical modelling data (with <100 µm voxel resolution) for temporal bone simulation (Wiet *et al.*, 2016).

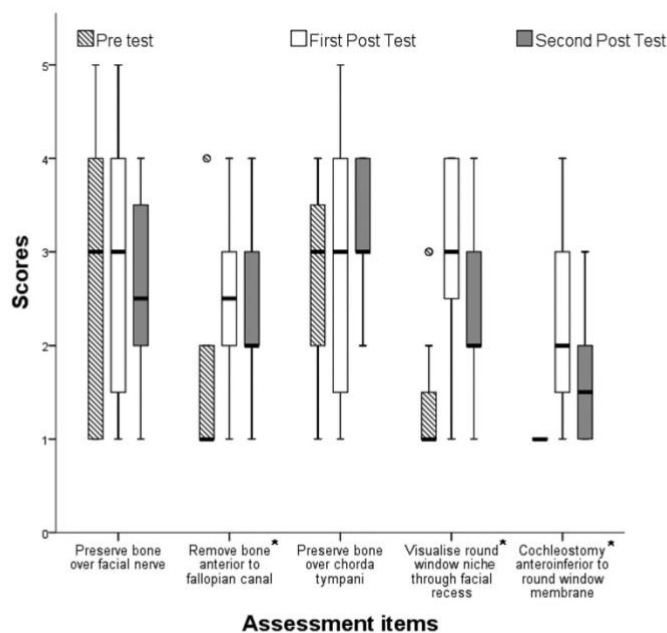


Figure 5 Cochlear implant competency task-based checklist assessment items in boxplot showing median and interquartile range, 90th percentile, circle denotes outliers. Significant differences were seen in the performance scores between pre-test to first post-test and pre-test to second post-test as indicated by asterisks except for the last item of location of the cochleostomy where significance was only seen between the scores of pre-test to first post-test.

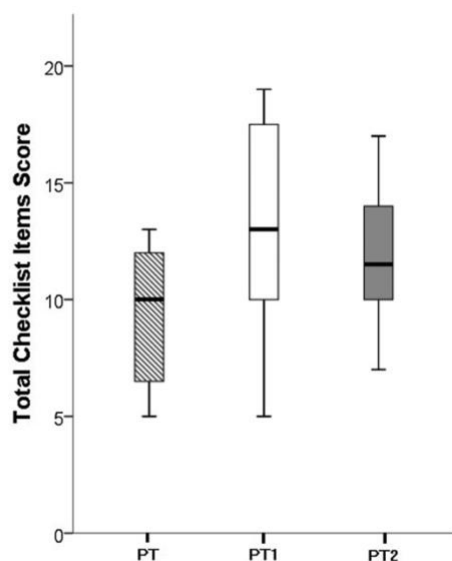


Figure 6 Total score of cochlear implant competency task-based checklist assessment items in boxplot showing median and interquartile range and 90th percentile. PT = pre-test, PT1 = first post-test, PT2 = second post-test. A significant difference was seen between the pre-test and both post-tests.

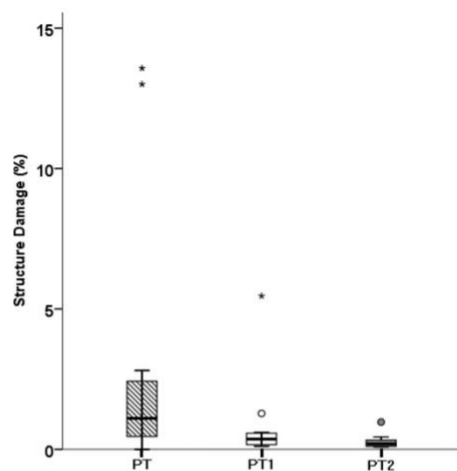


Figure 7 Boxplot showing median and interquartile ranges and 90th percentile for percentage (%) structural damage. PT = pre-test, PT1 = first post-test, PT2 = second post-test. A significant reduction in structural damage was seen between the pre-test and both post-tests.

In conclusion, this study clearly indicates that there is an improvement in performance of otolaryngology trainees after using a VR temporal bone simulator module for cochlear implantation. The otolaryngology

trainees showed a significant improvement with a large effect in global surgical performance, task specific outcomes and surgical safety. These data suggest that structured VR training modules to teach advanced otological procedures, that provide both real-time and summative feedback, can be effective in supplementing traditional training. Future research aims may be to investigate the long-term retention of these improvements and their transfer to the operating theatre.

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Chapter 4: Displaying acceptable electrode trajectories

Introduction

Skeletonisation of the facial recess is considered a necessary step in preparing the temporal bone for a cochlear implantation that preserves residual hearing (67, 68, 78). However, this practice is not followed by all cochlear implant surgeons (92). It has been suggested that that surgeons may not be confident with this procedure (79), presumed due to concerns for causing facial nerve injury surgery (103, 226-228).

Surgeons rely on an excellent understanding of the cochlea anatomy to correctly insert a cochlear implant electrode (97). Previous studies have referred to an optimal insertion vector to avoid insertional trauma of the electrode (86, 93), yet there may be minimal intraoperative visual cues to guide the surgeon as to the orientation of the cochlea for this optimal insertion (97).

The objective of this chapter was to investigate the effect of preparation of the facial recess on acceptable cochlear implant electrode trajectories. We also explored the effect of electrode diameter and surgical approach to the cochlea (RWM or cochleostomy) on acceptable implant trajectories. The aim was to provide surgeons with a practical aid to guide approaching the facial recess for cochlear implantation.

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Date: 20 Jan 2021
To: "Bridget Copson" bcopson@student.unimelb.edu.au
From: "Roland Laszig" sus.zapf@gmail.com
Subject: EAOR-D-20-02333R1

Ref.:
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 European Archives of Oto-Rhino-Laryngology

Dear Dr Copson,

I am pleased to tell you that your work has now been accepted for publication in European Archives of Oto-Rhino-Laryngology.

Comments from the Editor and Reviewers can be found below.

Thank you for submitting your work to this journal.

With kind regards

Prof. Dr. med. Roland Laszig
 Editor-in-Chief
 European Archives of Oto-Rhino-Laryngology

COMMENTS TO THE AUTHOR:

Reviewer #1: The authors have addressed the matters raised in my first review, with thanks.

—

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Surgical approach to the facial recess influences the acceptable trajectory of cochlear implantation electrodes

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Abstract

Purpose To provide practical guidance to the operative surgeon by mapping the location, where acceptable straight-line virtual cochlear implant electrode trajectories intersect the facial recess. In addition, to investigate the influence of facial recess preparation, virtual electrode width and surgical approach to the cochlea on these available trajectories.

Methods The study was performed on imaging data from eight cadaveric temporal bones within the University of Melbourne Virtual Reality (VR) Temporal Bone Surgery Simulator. The facial recess was opened to varying degrees, and acceptable trajectory vectors with varying diameters were calculated for electrode insertions via cochleostomy or round window membrane (RWM). The percentage of acceptable insertion vectors through each location of the facial recess was visually represented using heatmaps.

Results Seven of the eight bones allowed for acceptable vector trajectories via both cochleostomy and RWM approaches. These acceptable trajectories were more likely to lie superiorly within the facial recess for insertion via the round window, and inferiorly for insertion via cochleostomy. Cochleostomy insertions required a greater degree of preparation and skeletonisation of the junction of the facial nerve and chorda tympani within the facial recess. The width of the virtual electrode had only marginal impact on the availability of acceptable trajectories. Heatmaps emphasised the intimate relationship the acceptable trajectories have with the facial nerve and chorda tympani.

Conclusion These findings highlight the differences in the acceptable straight-line trajectories for electrodes when implanted via the round window or cochleostomy. There were notable exceptions to both surgical approaches, likely explained by the variation of hook region anatomy. The methodology used in this study holds promise for translation to patient specific surgical planning.

Keywords Cochlear implant · Electrode insertion vector · Electrode insertion trajectory · Optimal facial recess · Optimal insertion vector · Temporal bone surgery · Surgical training

Introduction

Electrode-induced cochlear trauma arises from contact between the electrode and internal cochlear structures, and can result in post implantation hearing loss [1–4]. To prevent intracochlear trauma, the ideal trajectory for all electrodes during implantation needs to be coaxial to the centreline of the scala tympani [5–9]. This trajectory is maintained

within the lower basal turn until the initial curvature is reached; in practice, this is approximately 5.5 mm [10, 11]. Previous studies have established that this straight-line optimal insertion vector is limited by the anatomy of the facial nerve within the facial recess and the orientation of the osseous spiral lamina at the initial segment of the basal turn (the hook region) [5–7]. In these studies, it has been demonstrated that not all temporal bones accommodate a straight-line trajectory into the scala tympani. In this context, surgical planning of an acceptable trajectory has been proposed and implemented in robotic cochlear implant surgery [12–16]. The co-registered image guidance of these robotic systems enables precise electrode placement. Without this novel technology, the operative cochlear implant surgeon relies on an excellent mental representation of the

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patients' cochlea anatomy [17] gained from pre-operative imaging and, where available, planning software [18, 19]. Furthermore, there is the question of skeletonisation of the facial recess. Arguments for thorough skeletonisation of the facial recess include improved visualisation of the round window [11, 13], as this is required to optimise the placement of the cochleostomy so as to avoid a scala vestibuli insertion [20]. While facial recess skeletonisation should ideally be complete, it has been recognised in the literature that many surgeons are not confident to complete dissection of the facial recess [21]. It has been suggested that the facial nerve should be adequately dissected to maximise the opportunity for an optimal insertion [22]; however, to the authors' knowledge, there have been no studies to date that have investigated the effect of skeletonisation of the facial recess on availability of appropriate electrode trajectories. Finally, with the aim of improving hearing preservation, a novel slim modiolar electrode has been introduced (Cochlear Ltd, Sydney Australia). This electrode has a unique insertion technique, where there is an external stiff sheath (of 0.8 mm width and 5.5 mm length) which holds the electrode in a straight line as it is inserted into the basal turn of the cochlear [10, 11]. While this electrode has shown promise with regards to hearing preservation, there are some concerns about tip fold-over and overall benefit compared to other electrode designs [23–25]. The insertion of a straight sheath is relatively novel, and presents particular challenges in trajectory of insertion and requires an extended round window approach for cochleostomy insertion [24]. In this study, we consider the operative surgeon's perspective and propose an approach to surgical planning that is generic for most electrode types and is of particular relevance to those inserted in a straight line such as the slim modiolar electrode. Specifically, we investigate the influence of surgical access into the cochlea (round window membrane (RWM) or cochleostomy), electrode diameter and thoroughness of the preparation of the facial recess upon the availability of straight-line trajectories. We explore how consideration of these factors can provide practical guidance to surgeons of varying experience in choosing the type of electrode and surgical approach for an individual patient.

Materials and methods

Setting

The platform used in this study was the University of Melbourne VR temporal bone surgery simulator. The temporal bones seen in this virtual platform were derived from manual segmentation of micro-computed tomography (micro-CT) grey scale data of eight cadaveric temporal bones without known pathology [26, 27]. The segmented structures

included the facial nerve, chorda tympani, RWM, scala tympani, scala vestibuli, malleus, incus, stapes, stapedius tendon, dura and sigmoid sinus. The osseous spiral lamina, spiral ligament and basilar membrane were segmented together as one structure and the semicircular canals and vestibule were segmented as one structure. The segmented anatomical structures are rendered in a virtual space to obtain a virtual model consisting of a surface mesh of each structure (including bone) [28]. A surface mesh represents an anatomical structure using a set of connected polygons (typically triangles) that form the outside surface of the structure. A haptic device that acts as the surgical drill provides force feedback and is used for removal of bone. During bone removal, the surface meshes are updated in real-time. When a surgeon performs virtual temporal bone surgery, the simulator continuously tracks which areas are removed at what time, allowing a precise recording of a surgical performance.

Defining surgical areas of interest

An expert otologist trained in cochlear implant surgery drilled eight virtual temporal bones to prepare for cochlear implantation. In particular, the otologist drilled the facial recess in various stages of exposure. The ideal surgical approach followed that described by Briggs et al., with complete skeletonisation of the facial nerve and wide dissection of the chorda tympani, allowing for complete visualisation of the round window niche and promontory [29]. An initial limited facial recess (Stage 1) was defined as the point at which the RWM was seen (including visualisation of the round window niche). Stage 2 is a further extension superiorly and inferiorly of this initial facial recess. Stage 3 is the area considered by an expert otologist to be a sufficiently skeletonised facial recess for implant insertion. For Stage 4, a final 'anatomic facial recess' was defined using the morphological operations of dilation and erosion [30] to include any voxels (3D points in space) between the facial nerve and chorda tympani with the superior extension to the level of the second genu of the facial nerve, adjacent to the fossa incudis (and to fill any holes between voxels in this area). With the surgically defined stages (1–3), the virtual temporal bone was drilled without underlying structures (such as the facial nerve, chorda tympani or cochlea) visualised until exposed surgically. In addition, the surgeon ensured that the incus buttress remained intact. The terminology "facial recess region" is used throughout the study and is defined as the three-dimensional area of bone removed and defined as the facial recess.

The cochleostomies were drilled by the expert otologist in a position that would be uniquely appropriate to that particular cochlea to allow for an appropriate insertion vector [17]. The expert surgeon had access to the full 3D model, and used this perspective to confirm that the cochleostomy was

in the correct position (in the scala tympani) as intended. The RWM and basal turn of the cochlea were defined by the anatomical segmentation of the micro-CT image and the otologist removed the bony overhangs of the niche in all eight virtual temporal bones when RWM insertions were studied.

Defining an acceptable electrode insertion vector

We defined an “acceptable” insertion vector as any straight-line trajectory that remains within the boundaries of the lower basal turn of the scala tympani for a length of 5.5 mm along the initial segment prior to contact with any intracochlear structure. The length of the initial segment of the basal turn of the cochlear is variable in length and has not been consistently defined [6, 31]. In this study, the distance of 5.5 mm was modelled on the length of the sheath of the insertion tool for a slim perimodiolar array as this length has been investigated and found to accommodate a range of cochlear sizes and anatomy [10]. An application was developed to explore electrode trajectories using data obtained from the VR simulator [32]. Using this application, straight-line “virtual electrode” vectors were mapped between the facial recess region and the scala tympani (Fig. 1). Varying diameters of a straight cylinder “virtual electrode” were then explored, from 0.4–1.2 mm in increments of 0.2 mm. These width values were arbitrarily chosen to represent a range of possible electrode arrays that would include either perimodiolar, mid-scalar or lateral wall designs. The acceptable trajectories were those that met the following assumptions:

- The distance between the area of the cochleostomy, where the virtual electrode passes and the area of entrance to the scala tympani should be less than 2 mm. This was to pre-

vent vectors passing from the cochleostomy and entering into the scala tympani at an area distant to the initial segment of the basal turn.

- The distance between the entry point of the vector into the scala tympani and contact with any intracochlear structure (lateral wall/modiolus/ OSL) should be at least 5.5 mm. This limited major misalignment of trajectory causing early collisions between the implant and the lower basal turn.
- Insertion vectors were considered coincident and removed, where the centre-point of the virtual electrode vector is within the distance of half a voxel (0.25 mm) of another virtual electrode vector at both the intersection of the facial recess region and at the entrance point to the scala tympani (either cochleostomy or RWM).
- The vectors should not pass through the basilar membrane/OSL/spiral ligament.
- The cylinder of a given diameter representing the virtual electrode is located fully within the boundaries of the facial recess and cochleostomy/round window regions.

Presentation of the results

The number of acceptable insertion vectors that pass through each voxel in the full facial recess was calculated and represented as a percentage with respect to the highest number of electrodes through any voxel. Heatmaps were used to graphically represent this. The trajectories were graded in frequency from 0–100% in four coloured categories, and corresponding Heatmap colours ranging from grey (no trajectories) to red (highest number of trajectories) were assigned to each voxel accordingly. The colour grading is from least to most trajectories—grey (no trajectories), green (1–33%), yellow (34–66%), red (67–100%). The number of acceptable virtual electrode insertion vectors in each stage of facial recess preparation was noted. These values give an indication of how precise the positioning of the virtual electrode within the facial recess needs to be. For example, if only two acceptable trajectories are available, the electrode requires extremely precise positioning, if there are one hundred trajectories available, the exact positioning within the facial recess is less critical. The region where these virtual electrodes intersect with the facial recess is visualised using the heatmaps. The percentage of the voxels within the full anatomic facial recess region that intersected with acceptable insertion vectors were also calculated.

Results

Stages of facial recess preparation

The facial recess was prepared in varying stages of exposure for all eight bones. The volumes of bone removed was

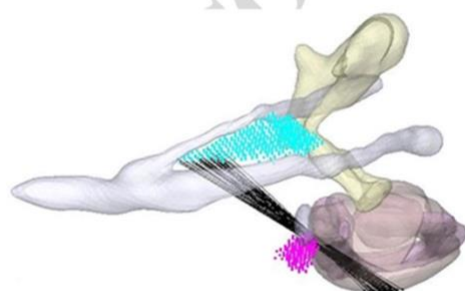


Fig. 1 Example of acceptable insertion vectors (black lines) via cochleostomy (magenta area which represents bone voxels drilled when performing cochleostomy, overlying bone removed for visualisation). Trajectories originate at the anatomic facial recess region (cyan)

variable between cases (Table 1). Figure 2 gives an example from Bone 6 of the four stages of exposure.

Position of available trajectories within the facial recess

Figures 3a–p and 4a–p show the Heatmaps of the anatomic facial recess regions when viewed from a lateral position (simulating the view seen on a surgical approach to the posterior tympanotomy). For a RWM approach, the acceptable trajectories tended to originate at the more superior aspect of the facial recess, adjacent to the incus buttress and abutting the facial nerve (Fig. 3a–o). When using the case-appropriate cochleostomy approach, the acceptable trajectories tended to be at the inferior part of the facial recess, adjacent to the junction of the chorda tympani and facial nerve (Fig. 4a–p).

Effect of the completeness of the facial recess preparation on available trajectories

In all eight temporal bones, the RWM was visualised through the posterior tympanotomy and stage 1 of the facial recess preparation was successfully performed. This corresponds to a grade 1a RWM accessibility using the St Thomas Hospital grading system [33]. In seven of the eight bones,

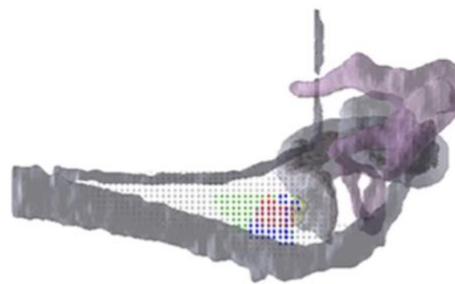


Fig. 2 Bone 6 stages of facial recess exposure. Red area=stage 1, red and blue area=stage 2, red, blue and green area=stage 3. Grey area shows the facial recess region which is the anatomic region of the facial recess

there were acceptable trajectories available via the RWM into the lower basal turn of the cochlea with the exposure of the facial recess at stage 1 (Fig. 5, Table 2). In the remaining bone (bone 2), there were no trajectories available via the RWM approach regardless of the stage of skeletonisation of the facial recess.

In bone 5, the stage of preparation of the facial recess had a marked effect on the availability of trajectories (Fig. 5).

Table 1 Total number of acceptable trajectories for round window membrane (RWM) insertions with varying diameter of the virtual electrode

Round window membrane approach									
FR preparation	Diameter (mm)	Bone 1	Bone 2	Bone 3	Bone 4	Bone 5	Bone 6	Bone 7	Bone 8
Stage 1 (initial)	0.4	365	0	599	416	69	851	974	3710
	0.6	307	0	487	337	64	678	830	3398
	0.8	265	0	416	279	54	560	742	3027
	1	203	0	313	211	46	448	614	2701
	1.2	150	0	235	150	40	368	532	2422
Stage 2 (suboptimal)	0.4	597	0	620	416	69	859	1229	5430
	0.6	490	0	504	337	64	683	1016	4941
	0.8	396	0	428	279	54	565	884	4356
	1	297	0	319	211	46	453	718	3879
	1.2	207	0	241	150	40	373	594	3419
Stage 3 (thorough)	0.4	598	0	764	459	470	859	1831	5511
	0.6	490	0	638	358	448	683	1460	4969
	0.8	396	0	553	300	423	565	1212	4366
	1	297	0	432	213	397	453	996	3882
	1.2	207	0	340	152	367	373	791	3419
Anatomic	0.4	598	0	828	523	656	1148	1882	7581
	0.6	490	0	698	385	577	919	1496	6536
	0.8	396	0	608	301	552	771	1243	5765
	1	297	0	476	214	443	617	1012	5015
	1.2	207	0	369	152	413	496	805	4361

FR preparation = facial recess preparation

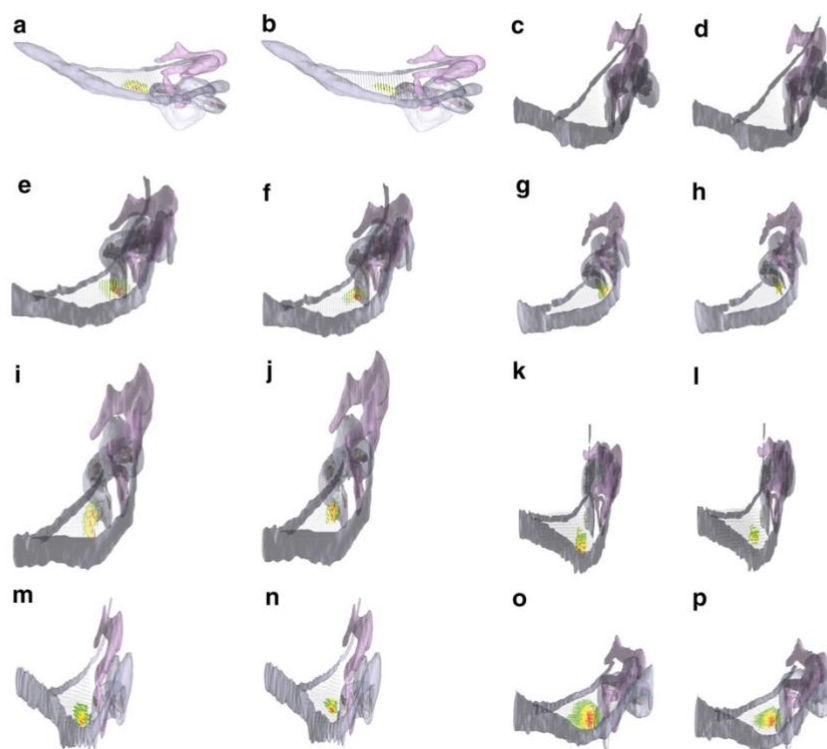


Fig. 3 Acceptable electrode insertion trajectories via RWM approach with virtual electrode diameter of 0.4 and 1.2 mm. Heatmaps of intersection of vectors with anatomic facial recess region with colours identifying percentage of acceptable trajectories within given areas. Grey=no trajectories, green=1–33% of acceptable trajectories, yellow=34–66% of acceptable trajectories, red=67–100% of acceptable trajectories. For simplification of visualisation the overlying bone (including the mastoid, incus buttress and promontory) has been removed. Orientation of images from the lateral perspective of a left temporal bone in supine lie

low=34–66% of acceptable trajectories, red=67–100% of acceptable trajectories. For simplification of visualisation the overlying bone (including the mastoid, incus buttress and promontory) has been removed. Orientation of images from the lateral perspective of a left temporal bone in supine lie

Electronic supplementary material 3 shows the areas of bone dissected for stage 1 of the facial recess preparation for bone 5. The region drilled was located anteriorly, in the superior facial recess, and abutted the chorda tympani. But the heatmap of the same bone (Fig. 3i,j), showed that the acceptable trajectories were found more posteriorly, closer to the facial nerve. This close relationship of the acceptable trajectory and the facial nerve has previously been identified [5] and holds true for all bones in this study. It is clear from this example that poor preparation of the facial recess precluded access to acceptable trajectories.

When the cochleostomy approach was assessed, three of the eight bones showed no available trajectories at stage 1 of the facial recess, and another three bones showed minimal numbers of available trajectories (Electronic supplementary material 1, Table 3). For the cochleostomy approach,

it was not until stage 3 preparation of the facial recess was performed that all eight temporal bones offered acceptable trajectories. This is represented in the heatmaps, where the available trajectories lie at the inferior aspect of the facial recess, adjacent to the junction of the facial nerve and chorda tympani (Fig. 4a–p). Bone 4 was the only bone, where the stage of preparation of the facial recess had a lesser impact on the available trajectories (Electronic supplementary material 1).

Effect of width of the electrode vector on available trajectories

There were very few cases, where the increased diameter of the virtual electrode vector influenced whether the temporal bone had any acceptable trajectories in a particular

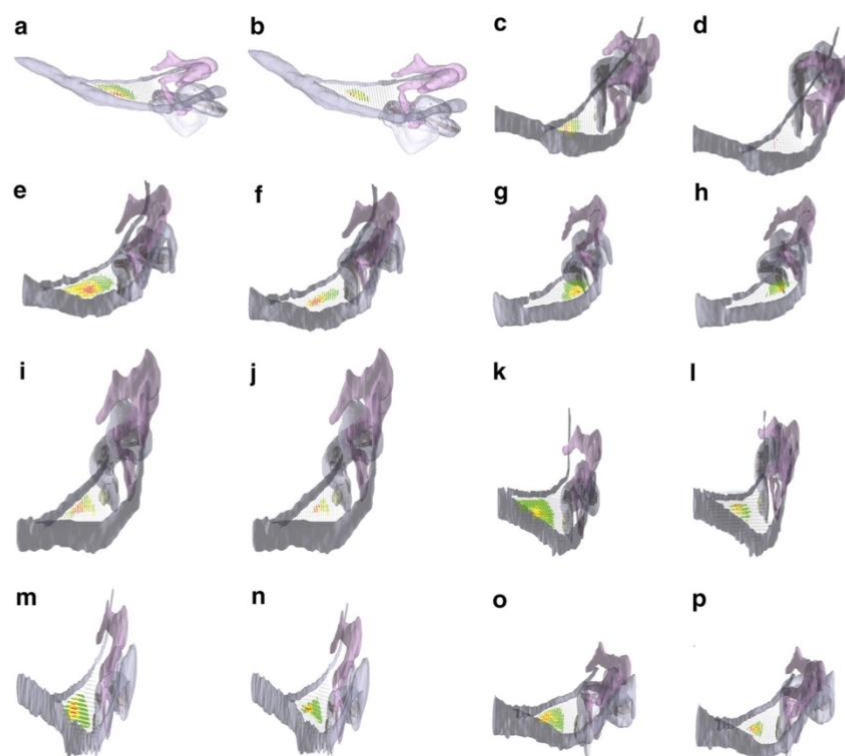


Fig. 4 Acceptable electrode insertion trajectories via cochleostomy approach with virtual electrode diameter of 0.4 and 1.2 mm. Heat-maps of intersection of vectors with anatomic facial recess region with colours identifying percentage of acceptable trajectories within given areas. Grey=no trajectories, green=1–33% of acceptable tra-

jectories, yellow=34–66% of acceptable trajectories, red=67–100% of acceptable trajectories. For simplification of visualisation the overlying bone (including the mastoid, incus buttress and promontory) has been removed. Orientation of images from the lateral perspective of a left temporal bone in supine lie

approach. Temporal bones numbered 2 and 3 with cochleostomy approaches were most affected by the increase in vector diameter (Table 3). In stage 1 and 2 of facial recess preparation for bone 3, where a cochleostomy approach was used, there was complete loss of the few available trajectories when the diameter was increased. Likewise, in all stages of facial recess preparation for Bone 2, where a cochleostomy approach was used, the increased width of the virtual electrode vector markedly reduced the available trajectories. The reduction in available trajectories was most prominent for diameters larger than 0.8 mm. A similar trend was seen in bone 6, with stage 2 of the facial recess preparation. The initial 50 acceptable trajectories that were available via a cochleostomy approach at 0.4 mm were reduced to 6 acceptable trajectories at 1.2 mm.

Variation in cochlear anatomy of the temporal bones

The eight temporal bones used had no known pathology. There was, however, anatomic variation between the bones. In particular, the anatomy of the hook region and orientation of the RWM varied. Electronic supplementary material 2 demonstrates variation in the hook region of four of the investigated temporal bones. Bones 2 and 4 had small hook regions and bone 6 and 8 had more prominent hook regions.

Fig. 5 Percentage of available trajectories via RWM in various stages of facial recess preparation, as compared to anatomic facial recess preparation. The diameter of the virtual electrode is 0.8 mm

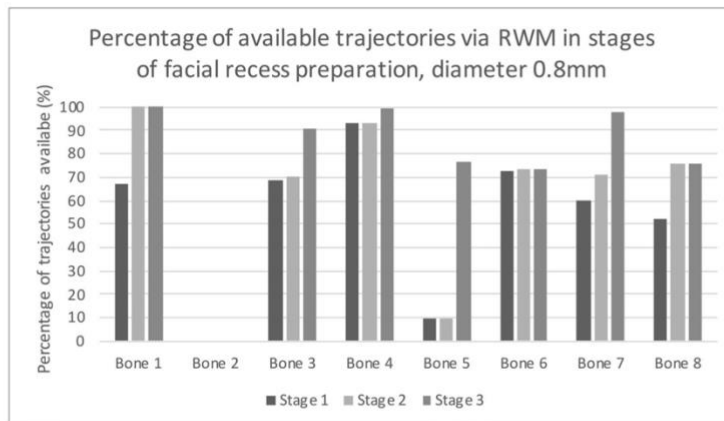


Table 2 Total number of acceptable trajectories for Cochleostomy insertions with varying diameter of the virtual electrode

Cochleostomy approach									
FR preparation	Diameter (mm)	Bone 1	Bone 2	Bone 3	Bone 4	Bone 5	Bone 6	Bone 7	Bone 8
Stage 1 (initial)	0.4	2	17	7	1259	0	0	153	0
	0.6	2	15	7	1040	0	0	153	0
	0.8	2	10	5	844	0	0	146	0
	1	2	6	2	671	0	0	133	0
	1.2	2	2	0	508	0	0	112	0
Stage 2 (suboptimal)	0.4	236	233	8	1497	0	50	484	927
	0.6	215	120	8	1278	0	29	438	850
	0.8	180	67	5	1082	0	12	396	751
	1	145	27	2	909	0	9	331	637
	1.2	124	2	0	701	0	6	252	496
Stage 3 (thorough)	0.4	927	551	1048	2183	100	3236	2544	2252
	0.6	795	238	868	1951	93	2694	2265	1864
	0.8	595	107	682	1660	80	2304	1916	1521
	1	413	27	510	1401	67	1771	1667	1128
	1.2	272	2	327	1072	58	1237	1312	732
Anatomic	0.4	1064	1217	6440	2632	233	11,285	8374	4743
	0.6	865	346	5139	2185	190	7640	6975	3017
	0.8	634	108	3959	1789	138	5325	5663	1968
	1	413	27	2893	1448	109	3708	4344	1211
	1.2	272	2	1870	1078	85	2158	2954	737

FR preparation = facial recess preparation

Discussion

Overview of results

The findings of this study support several generalisations. Firstly, variation of electrode diameter when ≤ 0.8 mm has

minimal effect on available trajectories. Secondly, acceptable trajectories via a RWM approach most frequently originate at the superior aspect of the facial recess, adjacent to the facial nerve. Finally, acceptable trajectories via a cochleostomy approach most frequently originate at the inferior aspect of the facial recess, adjacent to the junction of the facial nerve and chorda tympani and there is

Table 3 Volume of bone removed in various facial recess stages (Vol) and percentages of these areas compared to the anatomic facial recess area (% FR)

	Bone 1		Bone 2		Bone 3		Bone 4	
	Vol (mm ³)	% FR	Vol (mm ³)	% FR	Vol (mm ³)	% FR	Vol (mm ³)	% FR
Stage 1	4.07	52.02	0.83	14.36	1.95	23.13	2.06	24.33
Stage 2	5.39	68.82	1.60	27.67	2.25	26.71	2.62	30.93
Stage 3	6.59	84.17	1.89	32.75	3.37	39.98	4.23	49.90
Anatomic	7.83	100.00	5.77	100.00	8.43	100.00	8.48	100.00
	Bone 5		Bone 6		Bone 7		Bone 8	
	Vol (mm ³)	% FR	Vol (mm ³)	% FR	Vol (mm ³)	% FR	Vol (mm ³)	% FR
Stage 1	1.63	10.50	2.06	9.77	1.13	7.04	1.22	8.71
Stage 2	1.89	12.21	3.58	16.97	1.77	11.06	4.44	31.76
Stage 3	5.67	36.56	9.04	42.84	5.99	37.43	5.64	40.40
Anatomic	15.50	100.00	21.11	100.00	16.01	100.00	13.97	100.00

a noticeable effect of thorough preparation of the facial recess on available trajectories. However, these general trends did not apply to all of the eight temporal bones. In one bone (bone 2), there were no acceptable trajectories found via a RWM approach. In another bone (bone 4), the acceptable trajectories via a cochleostomy approach originated superiorly within the facial recess. These variations are not unexpected [34, 35] and are thought to reflect anatomic variations of the temporal bones, providing a strong case for undertaking surgical planning.

Round window membrane electrode insertion trajectories and facial recess preparation

Although round window insertions have been described as more challenging in cadaveric studies [10], our study has shown that for the purpose of following an acceptable electrode trajectory, that it is possible (but not advisable) to be less thorough when dissecting the interior part of the facial recess, at the junction between the facial nerve and chorda tympani (Table 2, Fig. 3). However, it remains imperative to skeletonise the facial nerve [21, 36], given that most trajectories about the facial nerve [5]. These results suggest that access to the cochlea via the round window may be more reliable than a cochleostomy approach, and may be of particular benefit, where precise angulation of the electrode is required in challenging cases [24].

Cochleostomy electrode insertion trajectories and facial recess preparation

We have seen that when a cochleostomy is used, the available trajectories are typically found near the junction of the facial nerve and chorda tympani, i.e., in the inferior part of the facial recess. These findings provide further reasons

to support the view that skeletonising the facial recess for optimising visibility of the round window and promontory is essential when implanting by cochleostomy [21, 29, 37]. We see that this is required not just to correctly place the cochleostomy, but to orient the electrode correctly as it enters the cochlea. Having an understanding of these possible challenges in cochleostomy approaches could help the operative surgeon with appropriate electrode choice. For example, given the size and ossification of the facial recess can be appreciated on pre operative CT, in cases of unfavourable anatomy, where more extensive dissection of the facial recess is expected, it may be appropriate to plan a round window trajectory.

Impact of electrode width on acceptable trajectories

Increasing the diameter of the virtual electrode from 0.4 to 1.2 mm reduced the area within the facial recess, where acceptable trajectories were found (Figs. 2, 4). For RWM insertions, increasing the diameter of a given electrode did not impact whether an acceptable trajectory was available, but did increase the precision of the orientation required to insert it, given there was a smaller area through which these trajectories passed. Conversely, in the cochleostomy approaches, there were several cases where increasing the electrode diameter above 1 mm markedly reduced the number of acceptable trajectories so much that there was no margin for error during electrode insertion (Table 2, bones 2, 5 and 6). These findings suggest that when inserted via a cochleostomy, electrodes with widths above 1 mm require precise trajectory orientation in a completely prepared facial recess to avoid intracochlear trauma. Thus, it is suggested that smaller electrode widths (0.8 mm or less) may be more appropriate for cochleostomy approaches, particularly for

surgeons uncomfortable with completely skeletonising the facial recess.

Variation of cochlea anatomy affects the location of acceptable virtual electrode trajectory within the facial recess

It is well documented that there is wide variation in the anatomy of the hook region [38–40]. Although this variability is unlikely to be accounted for in eight temporal bones, Electronic supplementary material 2 demonstrates some of the variations seen between these bones that are suggested to explain the variation in acceptable virtual electrode trajectories. For example, in bone 2, it is evident that there is a sharp rotation of the basal turn and OSL and a horizontally oriented RWM, which likely explains the absence of acceptable trajectories via a RWM approach. This finding concurs with the previous findings of Adunka et al., where the horizontal RWM orientation resulted in a more traumatic RWM insertion due to the cochlear hook causing electrode deflection [34]. In such cases, it is suggested that the orientation of the RWM is viewed intraoperatively, and when found to lie nearly horizontal, a cochleostomy approach may be preferred. Bone 4 has a very small, narrow hook region, the presence of which has been previously identified as a barrier to safe cochleostomy placement as there is less space under the spiral ligament [35]. However, the orientation of the OSL in bone 4 is in a horizontal plane, which is proposed to explain why despite the small hook region, there is room for a safe cochleostomy placement. This variation in rotation and orientation of the OSL has been previously reported [40–42] and this likely explains why the acceptable trajectories for bone 4 originate more superiorly in the facial recess than the cochleostomy approaches for the other bones.

Defining an acceptable virtual electrode trajectory

Previous authors have discussed cochlear implant electrode trajectories with relation to the ‘optimal’ trajectory [5]. The optimal trajectory has been defined as a line drawn coaxial to the centreline of the scala tympani [5], it has been previously identified that insertion vectors parallel to this centreline direction will be associated with less intra-cochlear trauma than electrodes following an unsuitable trajectory axis [43]. Despite this, some cochlear insertions with optimal trajectories penetrate the basilar membrane [43]. These observations highlight the limitations of trajectory calculation, because the physical properties of the cochlear electrodes itself, such as stiffness, unpredicted deformation and frictional forces will also influence the route taken once the electrode is within the cochlea [44]. Modelling of electrode properties and inclusion of these into a trajectory model would optimise the insertion quality further.

In this study we determined acceptable insertion trajectories available when an electrode array travelled in a straight line for 5.5 mm before contact with any internal structure (basilar membrane, osseous spiral lamina or lateral or inferior wall). This was adopted, because it reflects the “common path” of any electrode, irrespective of whether upon deeper insertion it hugs the lateral or the medial cochlear wall. These assumptions could be nuanced further, and refined for specific electrode designs. For example, gentle contact between the modiolar wall and a smooth but flexible electrode may be permissible.

Acceptable trajectory and surgical planning

The aforementioned anatomic variations may be suspected on pre-operative MRI or intraoperatively (as is for the case of RWM orientation); however, the integration of this anatomic detail into a surgical plan is a complex task for the cochlear implant surgeon [15]. This is another reason why surgical planning tools have been developed [18, 19, 45, 46]. Existing platforms rely on semi-automated segmentation for the accurate and detailed inner ear and facial nerve anatomy required for trajectory planning and this time-consuming process remains a rate-limiting step in the widespread use of patient specific planning platforms [19]. Moreover, most platforms focus on defining the optimal length of insertion rather than planning the optimal axis and position of insertion [18]. To date, trajectory planners remain research tools that are time and human resource consuming [12, 18, 45]. Furthermore, much of the previous literature in surgical planning has focused on an approach to support minimally invasive cochlear implant surgery [12–16]. Consequently, these platforms are unable to guide the operative cochlear implant surgeon to a practical approach to electrode trajectory planning as they require the insertion of fiducial markers [12]. By limiting the trajectory planning to the lower basal turn, this study provides a practical guidance to a common pathway of an electrode trajectory, regardless of electrode design. Using this methodology, the operative surgeon is guided to planning the unique facial recess dissection for the intended approach to the cochlear electrode insertion.

Limitations

Location of cochleostomy placement

In this study, an experienced cochlear implant otolaryngology surgeon defined and drilled the cochleostomy in the virtual temporal bones. Although these cochleostomies were consistently located antero-inferior to the round window, the exact location and volume of bone removed was variable between bones (Table 3). But we were confident that cochleostomy placement was appropriate for that bone, given that

the surgeon had access to the 3D temporal bone data at the time of cochleostomy placement, and was able to confirm that all were located appropriately, without causing damage to surrounding structures. Further exploration of the effect of cochleostomy position on acceptable trajectories was out of the scope of this study.

Variations in image orientation and resolution

The micro-CTs used for the preparation of the virtual temporal bones in this study showed variability in the orientation and matrix size of the image volumes. All measurements were performed in mm, and the matrix size variation was accounted for. The variation in specific orientation of the Figs. 3 and 4 are explained by this variation in orientation and matrix size.

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Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Bridget Copson, Sudanthi Wijewickrema, Xingjun Ma, Yun Zhou, Jean-Marc Gerard and Stephen O'Leary. The first draft of the manuscript was written by Bridget Copson and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Availability of data and material On contact of corresponding author.

Code availability On contact of corresponding author.

Compliance with ethical standards

Conflicts of interest The authors have no conflicts of interest to disclose.

Ethical approval Ethical approval was given by the Royal Victorian Eye and Ear Hospital Ethics Committee (17-1313H).

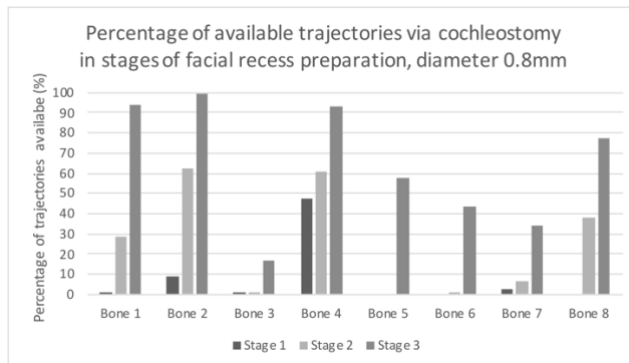
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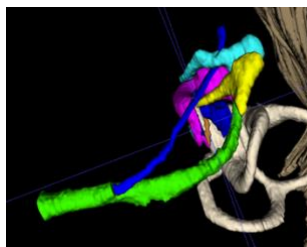
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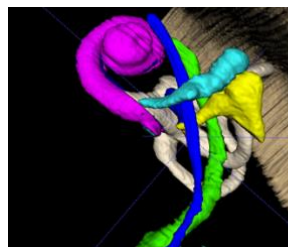
Electronic supplementary material 1: Percentage of available trajectories via cochleostomy in various stages of facial recess preparation, as compared to anatomic facial recess preparation. The diameter of the virtual electrode is 0.8mm.



Electronic supplement material 2 : Three dimensional rendered segmentations of Bones 2, 4, 6, 8 in orthogonal views showing the variation in hook region anatomy. Cochlea = magenta, RWM = teal, OSL/basilar membrane/spiral ligament = blue, facial nerve = green, chorda tympani = blue, semicircular canals and vestibule = cream, incus = yellow, malleus = aqua, stapes = blue, stapedius tendon = orange, dura = sand, sigmoid = light teal.



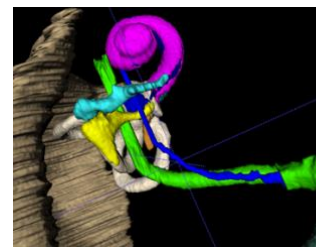
ESM 2a Bone 2 lateral view



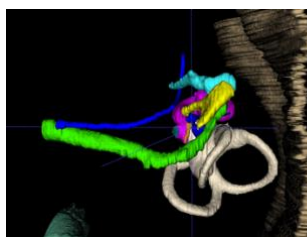
ESM 2b Bone 2 anterior view



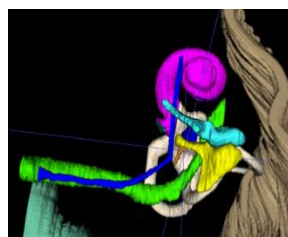
ESM 2c Bone 4 lateral view



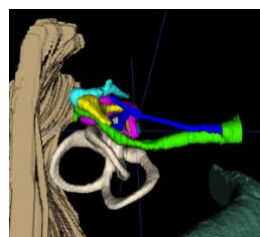
ESM 2d Bone 4 anterior view



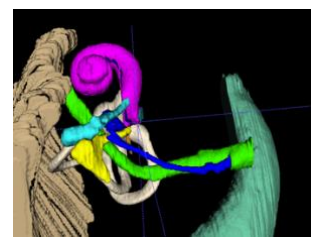
ESM 2e Bone 6 lateral view



ESM 2f Bone 6 lateral view

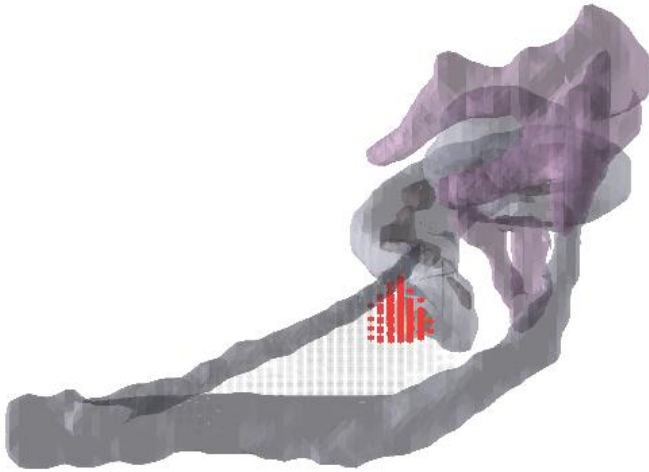


ESM 2g Bone 8 lateral view



ESM 2h Bone 8 lateral view

Electronic supplement material 3: Bone 5 stage 1 of facial recess exposure. Light grey area shows the facial recess region which is the anatomic region of the facial recess.



Chapter 5: General Discussion

The studies conducted in this thesis were undertaken to explore the possible role of virtual reality simulation in temporal bone anatomy education and surgical training. The findings will help inform the future of anatomy and surgical training in temporal bone education. This thesis lies in the wider context of improving outcomes for post cochlear implantation hearing loss, where it has been identified that precise surgical technique is imperative in performing hearing preservation cochlear implant surgery (112, 118). Precise technique requires an excellent understanding of both the operative procedure and the relevant three-dimensional temporal bone anatomy (229). In contemporary anatomy and surgical education there has been both a reduction in dedicated training hours as well as ongoing high expectations for performance (1-5). Virtual reality simulation has been marked as a promising adjunct in anatomy and surgical training with its unique ability to combine risk free and repetitive practice, interactive three-dimensional content and positive subjective experience (150).

These benefits of virtual reality simulation were seen in the first study of this thesis, where the development of a clinically oriented temporal bone anatomy module was undertaken (**Chapter 2**). An initial pilot study of 20 participants was performed to evaluate the effectiveness of this temporal bone anatomy module and compare two dimensional (PPT) three-dimensional (VR) display technologies. A post tutorial survey demonstrated that both groups were positive in their subjective review of the module (perceived effectiveness: PPT median 4 (IQR 1), VR median 4.5 (IQR 1), $p = 0.003$). The VR group were significantly more confident in their understanding of the anatomy (PPT median 3 (IQR 1), VR median 4 (IQR 0), $p = 0.008$). Given the positive response to the developed anatomy module, a further randomised control study was performed to compare three display modalities (two dimensional = PPT, monoscopic three dimensional VR = M3D, and stereoscopic three-dimensional VR = S3D). The questionnaires used in the pilot study were analysed for difficulty and effectiveness in discriminating participants' knowledge. In the absence of a standardised curriculum, selected questions which showed adequate difficulty and discrimination ability were collated to form questionnaires used in the subsequent studies. In this study there was a pre-, post-tutorial and 6 week retention anatomy questionnaires in addition to a subjective experience survey. There were 47 participants included in the study. The temporal bone anatomy module was found to be effective, with a large effect size ($p = <0.005$, Cohen's d 1.41). This improvement was maintained at the 6 week mark ($p = <0.005$, Cohen's d 0.83). The students showed improved confidence in understanding of 3D temporal bone anatomy ($p = 0.001$), felt better prepared for a clinical rotation in otolaryngology ($p = 0.006$), and were more interested in otolaryngology as a career pathway ($p = 0.017$).

While the anatomy module was clearly effective for the whole group, the display technology used had less consistent benefits and did not affect the majority of the knowledge learning outcomes. The S3D display demonstrated significant benefit compared to the PPT display for clinical and spatial relation domain questions in the immediate period ($p = 0.01$). However, this benefit was not sustained to the retention test at 6 weeks. Despite these mixed results, the two 3D groups were found to be subjectively superior in perceived effectiveness ($p = 0.004$), ease of use ($p = 0.024$) and usability ($p = <0.005$).

In summary, the clinically oriented temporal bone anatomy module developed was effective as a self-directed teaching module. It was also effective as an educational tool for the alternative outcomes of anatomy education such as interest and preparedness for clinical work in

otolaryngology. The subjective experience of this module delivered with a 3D display was superior to that of the 2D version, however both were appropriately effective for imparting anatomical knowledge.

We envision that this would become the first module in a series of training in otolaryngology. Once familiar with the VR simulation set-up, the student could revisit the module as required during medical school and return to use the same simulator set up for the more advanced modules discussed forthwith. Its content could even be adapted to form an assessment for potential candidates applying for surgical training, where basic anatomic competency is assured prior to commencement of training.

The display modality to apply to this module in practice would depend on the resources available at a given medical school and the desired outcomes of the module. Alternatively, in a resource poor setting, the anatomy module could be displayed in a 2D format and still provide an effective learning tool.

Following the success of the temporal bone anatomy module and given the positive participant feedback, a further module for training advanced temporal bone surgery was developed (Chapter 3). We identified and reiterated the efficacious components used in the first module such as visual and auditory feedback, pre-tutorial simulation orientation and a step-by-step instruction which was assessed using a pre and post-test assessment design. The assessment tool used in this study replicated the step-by-step design with a task based checklist as well as a global rating scale. Other components of the module were novel, we provided performance goals by combining concurrent and terminal feedback so that the participant's end product was automatically compared to the same temporal drilled by an expert otologist. To avoid participant reliance on feedback for performance, we also enabled more user preferences by integrating both an "instruction" mode where feedback was given and a "practice" mode without feedback.

In the assessment, the registrars completed the dissection of a virtual temporal bone from the stage of cortical mastoidectomy through to drilling of a cochleostomy or preparation of the round window. There was a significant improvement with a large effect size in global rating scales between the baseline assessment and both post-tutorial dissections (Pre-Test to Post-Test1 $p=0.026$, $r = 0.642$), (Pre-Test to Post-Test 2 $p = 0.003$, $r=0.848$). There was also a significant Improvement in the total scores of the task-based checklist with large effect sizes (Pre-Test to Post-Test 1 $p= 0.008$, $r =0.77$; PT to PT2 $p = 0.027$, $r =0.638$). In addition, a significant reduction in inadvertent anatomic structural damage with a large effect sizes (Pre-Test to Pre-Test 1 $p=0.023$, $r=0.657$; Pre-Test to Post-Test 2 $p=0.010$, $r=0.747$) was observed. The steps of the checklist that showed greatest improvement were removing bone anterior to the fallopian canal, visualisation of the round window niche through the facial recess and drilling of the antero-inferior cochleostomy. One step that showed little improvement throughout this study was the step of preservation of bone over the facial nerve and chorda tympani.

The findings of this study encourage the use of virtual reality simulation for training the advanced temporal bone procedure of preparation for cochlear implantation. Furthermore, automated guidance was successfully used to approximate the participant's surgical technique to that of an expert. The findings suggest that the methodology of using a dataset of experts performing a surgical procedure could be used for other advanced temporal bone procedures.

This educational module was effective in training particular steps of cochlear implant surgery such as opening the facial recess to visualise the round window membrane niche, removing bone from the

fallopian canal and drilling of an antero-inferior cochleostomy. These particular steps are pertinent in reducing surgical trauma, and for preparing the temporal bone for a cochlear implantation that preserves residual hearing. This module has the potential to improve a surgeon's confidence in skeletonising the facial recess while minimising damage to structures such as the facial nerve. It also has the potential to be nuanced further, to integrate other particular areas of surgical technique important for hearing preservation cochlear implantation. This could include a visual guide of the areas within the facial recess that provide an acceptable virtual electrode insertion as described in **Chapter 4**. The limitation of the simulator with regards to the limits of exposure of the facial nerve and chorda tympani also raised a broader discussion on the necessity of complete skeletonisation of the facial recess. This was also explored in **Chapter 4**, along with an investigation of the relationship of a virtual electrode trajectory to both the chorda tympani and facial nerve.

The application of this module also lends itself to the training of both otolaryngology trainees, as well as a platform for otolaryngology surgeons for the use of mastering specific skills (preparing the temporal bone for cochlear implant surgery). Furthermore, given the terminal feedback comparing the user's performance to an expert performance and task-based assessment on surgical steps, this module could also be used as an accreditation tool to define scope of practice.

Finally, to explore the use of the simulation data in providing practical guidance to surgeons during cochlear implant surgery, a study using the segmented anatomy of micro computed tomography scans of eight human cadaveric temporal bones was performed. A program was devised where a virtual electrode with various diameters was applied to the simulation platform data. Acceptable insertion vectors were calculated, and heat maps were used to display the areas within the facial recess that provided acceptable insertion vectors into the initial segment of the basal turn of the cochlea. For round window membrane approaches, the acceptable trajectories generally intersected the facial recess at its superior aspect, with a close relationship to the facial nerve. For the cochleostomy approaches, the acceptable trajectories were most likely to intersect the facial recess at its inferior aspect, with a close relationship to the junction of the facial nerve and chorda tympani.

The degree of facial recess preparation had a greater impact on the availability of acceptable trajectories via a cochleostomy than a round window membrane approach. An initial stage of facial recess preparation was described as the removal of bone within the facial recess sufficient to visualise the round window membrane. This stage of exposure was successful in all eight temporal bones. This initial stage of exposure was sufficient to expose acceptable trajectories for all seven bones where any acceptable trajectories were possible with a round window membrane approach. Comparatively, when a cochleostomy approach was used, only two temporal bones allowed acceptable insertion trajectories with the initial stage facial recess preparation. The remainder of the temporal bones required an expert performed skeletonised facial recess to provide access for acceptable electrode trajectories. It was also found that the variation in width of the virtual electrode between 0.4mm and 0.8mm had minimal effect on the presence of acceptable electrode trajectories. Variation of electrode width between 0.8mm and 1.2mm had more impact on electrodes inserted via cochleostomy than round window membrane approaches.

This data can be used to inform surgical technique with the aim of minimising insertion trauma for cochlear implantation. We envision that the visual display of this data could be implemented in a virtual reality simulator cochlear implantation module for training electrode insertion technique. Further directions for future studies are discussed forthwith.

Implementation of novel virtual reality educational modules

The efficacy of novel simulator modules in virtual reality education forms only part of the evidence for the implementation of virtual reality platforms in anatomy and/or surgical training. Despite a growing evidence body of the benefits of simulation based training in surgical and anatomy education, these technologies have been slow to be adopted into mainstream medical education (142, 230, 231). While cadaveric temporal bone dissection courses remain the main modality for temporal bone education, virtual temporal bone simulators are increasingly available to surgical trainees (158, 159). However, the presence of these simulators does not guarantee their effective use (232). Chang et al. assessed utilisation of a laparoscopic simulator after an initial introductory session and found only 31% of trainees returned within a 3 month period despite granting after-hours access (233). They concluded that participation should be made mandatory or at least protected teaching time should be afforded to residents for the purpose of simulation training. The effect of combining a mandatory training requirement was assessed by Frendo et al. who found that a convenient, de-centralised VR temporal bone simulator was better utilized when combined with mandatory training requirements than on a volunteer basis. Furthermore, the study suggested that motivating factors for using simulation training were the participant understanding the positive benefits of the VR training as well as a subjective awareness of skill progression (232). Based on the findings of a literature review, Fischer et al. have suggested the integration of a step-wise approach to temporal bone surgical training where simulation training is undertaken with intermittent structured assessments (234). Further studies to outline the overall value of these temporal bone simulators could also include investigations of the benefits to patient care and the applicability to ongoing learning for established surgeons.

Standardised anatomy curriculum

There is currently no standardised anatomy curriculum in Australia (230) and in **Chapter 2**, the anatomy module was developed by compiling clinically oriented anatomy material to an appropriate standard as indicated by an expert otolaryngologist. Integral to the ongoing development and application of temporal bone simulators into medical education in Australia is the development of a standardised curriculum for temporal bone anatomy. While there may be varying opinion as to what would be considered core content for pre-clinical education (235), a curriculum could be developed with content of graduating levels of difficulty. This would lend itself to delivery of modules that could be used at progressive levels of trainee education (this has previously been referred to as a vertical approach) (236). Alternatively, a foundation anatomy curriculum could be developed with the option of specialty-specific advanced anatomy courses as proposed by Wong et al. (237).

Patient specific rehearsal and automatic segmentation

The currently available temporal bone simulators are based on a set of cadaveric temporal bones (238). While there has been a push to include anatomic variation in the dataset available for trainees (53), there have been few studies evaluating patient-specific rehearsal in VR temporal bone simulation. Patient-specific rehearsal using a virtual reality platform has been shown to reduce intra-operative errors in endovascular aortic aneurysm repairs (239). Preliminary experience with a patient specific skull base VR simulator has demonstrated excellent correlation to intraoperative findings as well as positive subjective evaluation (240). In the field of otology, Locketz et al. have shown the improved confidence of trainees who undertook cadaveric specific virtual rehearsal (241). To the author's knowledge there are currently no temporal bone simulators capable of integrating patient-specific datasets.

The limited development in this area is presumed related to the challenges in automatic segmentation of temporal bone images. The aforementioned patient-specific simulators used in vascular, skull base and temporal bone simulators to date remain dependent on at least partial manual segmentation. However, manual segmentation of a temporal bone is time inefficient and impractical for routine use. There have been preliminary studies in otology with promising results with regards to time taken to segment the temporal bone, but these simulators are limited in face validity, especially for inner ear and soft tissue structures (242, 243). The complex anatomy of the temporal bone in a small contained region presents a further challenge for automated segmentation algorithms compared to other anatomic structures. Despite this, there have been recent advances in this arena. A recent study describes the algorithms for automatic segmentation of high resolution micro-computed tomography scans, with promising results of facial nerve segmentation (244).

A further limiting factor inhibiting the development of patient specific training modules is the transferability of automated feedback systems. At the moment, these are mapped for each individual temporal bone module, and further work is required to attempt to develop generalised algorithms for automated feedback (245). Once these issues are addressed, patient specific rehearsal would have the potential to revolutionise surgical training. Not only would there be the capacity for educational modules with a large range of anatomic variations, but educators could in addition use VR simulation to ensure trainee competence prior to the commencement of operative training. Further studies in this area could then determine effectiveness of patient specific training on patient outcomes.

Conclusion to Thesis

In this thesis, we explored the further use of virtual simulation in temporal bone anatomy and surgery by developing and validating two novel virtual reality simulator modules. We found that the clinically oriented temporal bone anatomy module improved medical students' subjective and objective understanding of temporal bone anatomy and clinical understanding. The advanced temporal bone surgery module improved trainee performance to both a previously encountered temporal bone and also a novel temporal bone dissection. The simulator data was also found to be useful in modelling acceptable virtual electrode trajectories into the cochlea, findings that provide a practical guide for cochlear implant surgeons.

These insights encourage the ongoing use of virtual reality simulation in temporal bone education. Furthermore, these findings suggest that the VR temporal bone simulator has application to multiple stages of medical education and is of benefit to medical students, junior doctors and surgeons alike. This VR temporal bone simulator would therefore be appropriately used in a vertical style approach to learning where the simulator is revisited during training of foundation anatomy, specialty-specific anatomy, basic and advanced temporal bone procedural training.

Chapter 6: Publications and presentations

Publications included in this thesis

Copson B, Wijewickrema S, Zhou Y, Piromchai P, Briggs R, Bailey J, Kennedy G, O'Leary S. Supporting skill acquisition in cochlear implant surgery through virtual reality simulation. *Cochlear implants international*. 2017 Mar 4;18(2):89-96.

Wijewickrema S, Copson B, Ma X, Briggs R, Bailey J, Kennedy G, O'Leary S. Development and validation of a virtual reality tutor to teach clinically oriented surgical anatomy of the ear. 2018 IEEE 31st International Symposium on Computer-Based Medical Systems (CBMS) 2018 Jun 18 (pp. 12-17). IEEE.

Copson B, Wijewickrema S, Sorace L, Jones R, O'Leary S. Development of a virtual reality clinically oriented temporal bone anatomy module with randomised control study of three-dimensional display technology. *BMJ Simulation and Technology Enhanced Learning*. 2020 Dec 14:bmjstel-2020.

Copson B, Wijewickrema S, Ma X, Zhou Y, Gerard JM and O'Leary S. Surgical approach to the facial recess influences the acceptable trajectory of cochlear implantation electrodes. *European Archives of Oto-Rhino-Laryngology*. Accepted 21 Jan 2021.

Co-authored publications submitted during this thesis

Wijewickrema S, Copson B, Zhou Y, Ma X, Briggs R, Bailey J, Kennedy G, O'Leary S. Design and evaluation of a virtual reality simulation module for training advanced temporal bone surgery. In 2017 IEEE 30th international symposium on computer-based medical systems (CBMS) 2017 Jun 22 (pp. 7-12). IEEE.

Ma X, Wijewickrema S, Zhou Y, Copson B, Bailey J, Kennedy G, O'Leary S. Simulation for training cochlear implant electrode insertion. In 2017 IEEE 30th International Symposium on Computer-Based Medical Systems (CBMS) 2017 Jun 22 (pp. 1-6). IEEE.

Ioannou I, Zhou Y, Wijewickrema S, Piromchai P, Copson B, Kennedy G, O'Leary S. Comparison of experts and residents performing a complex procedure in a temporal bone surgery simulator. *Otology & Neurotology*. 2017 Jul 1;38(6):e85-91.

Wijewickrema S, Zhou Y, Ioannou I, Copson B, Piromchai P, Yu C, Briggs R, Bailey J, Kennedy G, O'Leary S. Presentation of automated procedural guidance in surgical simulation: results of two randomised controlled trials. *The Journal of Laryngology & Otology*. 2018 Mar;132(3):257-63

Presentations arising from this work

2016 A qualitative assessment of participant experience in virtual reality simulation for advanced temporal bone training, 14th Australasian Auditory Neuroscience Workshop, Hobart, Tasmania

2016 Effectiveness of automated procedural guidance in virtual reality temporal bone surgery, 14th Australasian Auditory Neuroscience Workshop, Hobart, Tasmania

2016 The effectiveness of a virtual reality temporal bone surgery simulation in training cochlear implant surgery, University of Melbourne, Department of Surgery Research Day, Melbourne, Victoria

2016 Do experts practice what they preach: A study of variability in expert performance of temporal bone surgery, 53rd Annual Scientific Meeting of the Surgical Research Society of Australasia, Melbourne, Victoria

2020 Development of a virtually reality clinically oriented temporal bone anatomy module with randomised control study of presented three-dimensional display technology. Biomed Link 2020, Melbourne, Victoria.

2021 Developing a novel virtual reality simulation temporal bone anatomy module and are three-dimensional display technologies required. Podium presentation, 44th annual midwinter meeting of the association for research in otolaryngology, virtual conference.

2021 Surgical Approach to the Facial Recess Influences the Acceptable Trajectory of Cochlear Implantation Electrodes. Poster presentation, 44th annual midwinter meeting of the association for research in otolaryngology, virtual conference.

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