Supporting Skill Acquisition in Cochlear Implant Surgery through Virtual Realty Simulation

Bridget Copson (MBBS (Hons)) [1]

Sudanthi Wijewickrema (BEng (Hons), PhD) [1]

Yun Zhou (BSc, MSc, PhD) [1]

Patorn Piromchai (MD, MSc, FRCOT, FICS) [1,2]

Robert Briggs (MBBS, FRACS) [1]

James Bailey (BEng, PhD) [3]

Gregor Kennedy (BA (Hons), PhD) [4]

Stephen O'Leary (MBBS, BMedS, PhD, FRACS) [1]

1. Department of Surgery (Otolaryngology), University of Melbourne, Australia

2. Department of Otorhinolaryngology, Khon Kaen University, Thailand

3. Department of Computing and Information Systems, University of Melbourne, Australia

4. Melbourne Centre for the Study of Higher Education, University of Melbourne, Australia

Corresponding Author:
Bridget Copson
ORCID: 0000-0001-7307-8229
Department of Otolaryngology, University of Melbourne,
Level 5, Royal Victorian Eye and Ear Hospital,
32, Gisborne Street, East Melbourne, VIC 3002,
Australia
Tel - +61 3 9929 8365
Email – bridgetcopson@gmail.com

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Objectives

To evaluate the effectiveness of a virtual reality 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 virtual reality 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 ranked 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 virtual reality simulation with automated guidance can effectively be used to train surgeons in training complex temporal bone surgeries such as cochlear implantation.

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, Tykocinski, Stidham, & Roberson, 2005; Meshik, Holden, Chole, & Hullar, 2010). Either approach requires good visualisation 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, Wright, & Isaacson, 2007; Shapira, Eshraghi, & Balkany, 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 skeletonisation of the facial nerve and chorda tympani in the facial recess and visualisation 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., 2011; Duckworth, Silva, Chandler, Batjer, & Zhao, 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, Stredney, & Wan, 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, Cook, Zendejas, Hamstra, & Brydges, 2014; Laeeq et al., 2009; Wiet et al., 2011; Yi Chen Zhao, Kennedy, Yukawa, Pyman, & O'Leary, 2011; Zirkle, Roberson, Leuwer, & Dubrowski, 2007) .

Virtual reality (VR) simulation trainers facilitates skills acquisition and transfer of these to the operating 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, Arora, Singh, Tolley, & Darzi, 2012; Sewell et al., 2008; Wiet et al., 2012; Yi C Zhao, Kennedy, Hall, & O'Leary, 2010; Yi C Zhao, Kennedy, Yukawa, Pyman, & O'Leary, 2011), 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 Modeolar 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 (Yi C Zhao et al., 2010; Yi C Zhao et al., 2011; Yi Chen Zhao et al., 2011). The virtual temporal bones were derived from microcomputed tomography of cadaveric temporal bones (Yi C Zhao et al., 2011), from which anatomical structures had been segmented manually, rendered in 3D and visualised 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

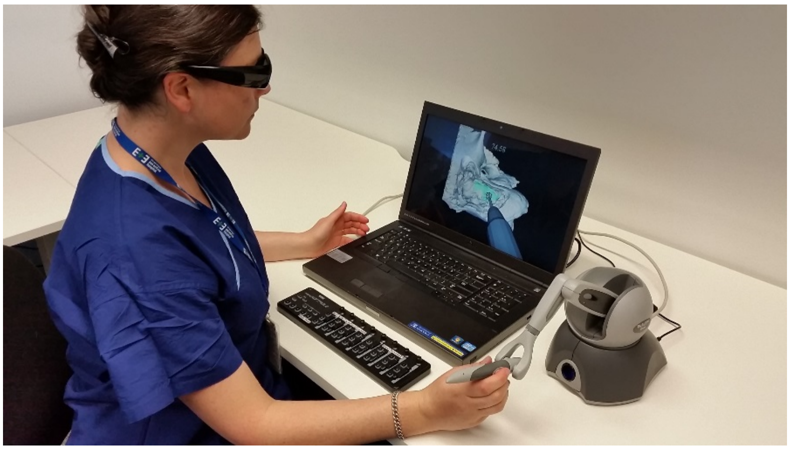

Figure 1: A surgeon using the University of Melbourne VR temporal bone surgery simulator to perform cochlear implant surgery. Components of the simulator include the commercially available laptop, haptic device and midi attachment.

midi attachment. Using the University of Melbourne VR temporal bone surgery simulator, a surgeon can perform middle and inner ear operations. Figure 1 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 skeletisation of the facial nerve and chorda tympani to optimise 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 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.

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 skeletonise 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 bur to continue drilling

the facial recess or use a larger burr to take more bone off the ear canal wall to improve visualisation of the round window through the facial recess
Reduce burr size to perform cochleostomy. Typically a 0.8-1mm diamond burr on a tapered shaft is preferred. Rotate the bone to view in the direction of the basal turn. Skeletonise the inferior border of the round window membrane, saucerise the adjacent bone, and drill a cochleostomy into the scala tympani
You have successfully completed the procedure. You can now place the electrode

Participants:

These were twelve 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 familiarise 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.

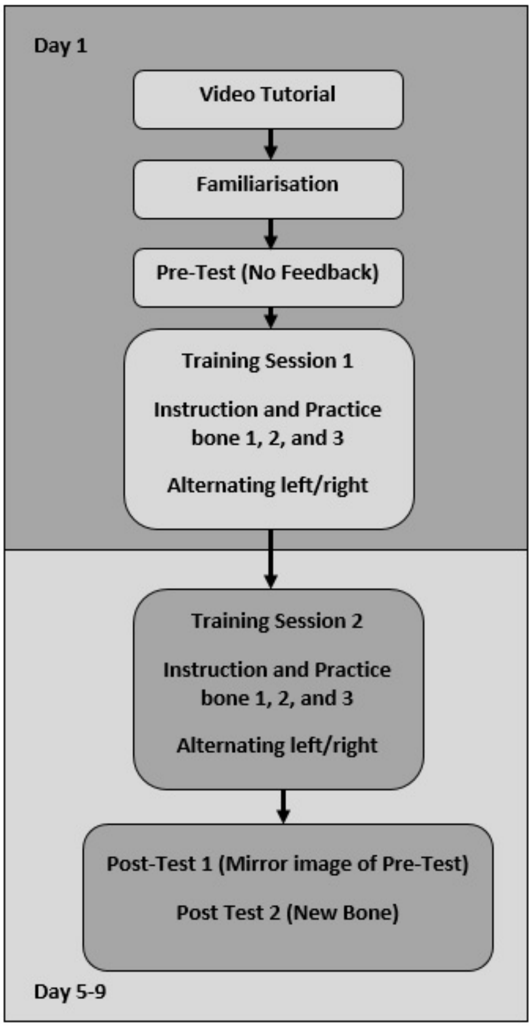

Figure 2: Flow diagram of study design

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; Yi C Zhao et al., 2011; Yi Chen Zhao et al., 2011) and the task based checklist of surgical steps was synthesised 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/square root of N). A small effect is represented by an r score of 0.1, 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 3 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.

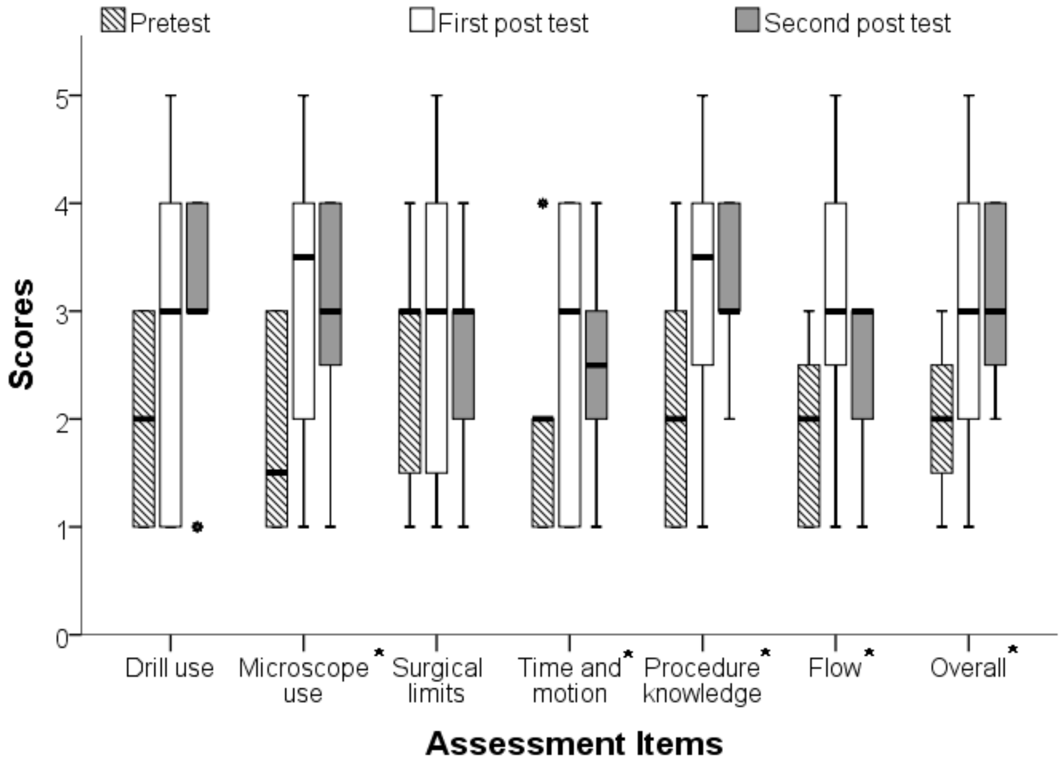

Figure 3: Global rating scale assessment items in boxplot showing median and interquartile range and 90th percentile, circle denotes outliers. Significant differences were observed in the items indicated by an asterisk. p values included in Table 2.

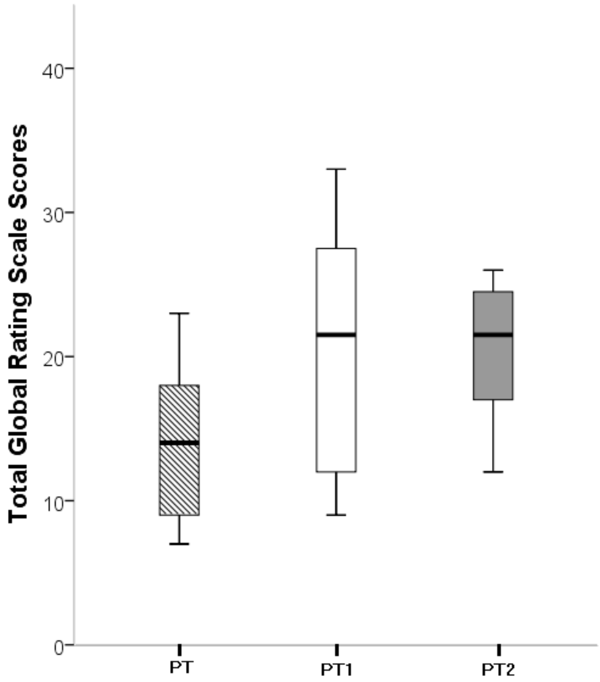

Figure 4: Combined score of global rating scale assessment items in boxplot showing median and interquartile range and 90th percentile. Comparison between pre-test (PT) and both the post-tests (PT1 and PT2) were significant with large effects. p values included in Table 2.

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 PT 1 $p=0.008$, $r=0.77$; 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, visualisation of the round window niche through the facial recess and drilling of the cochleostomy.

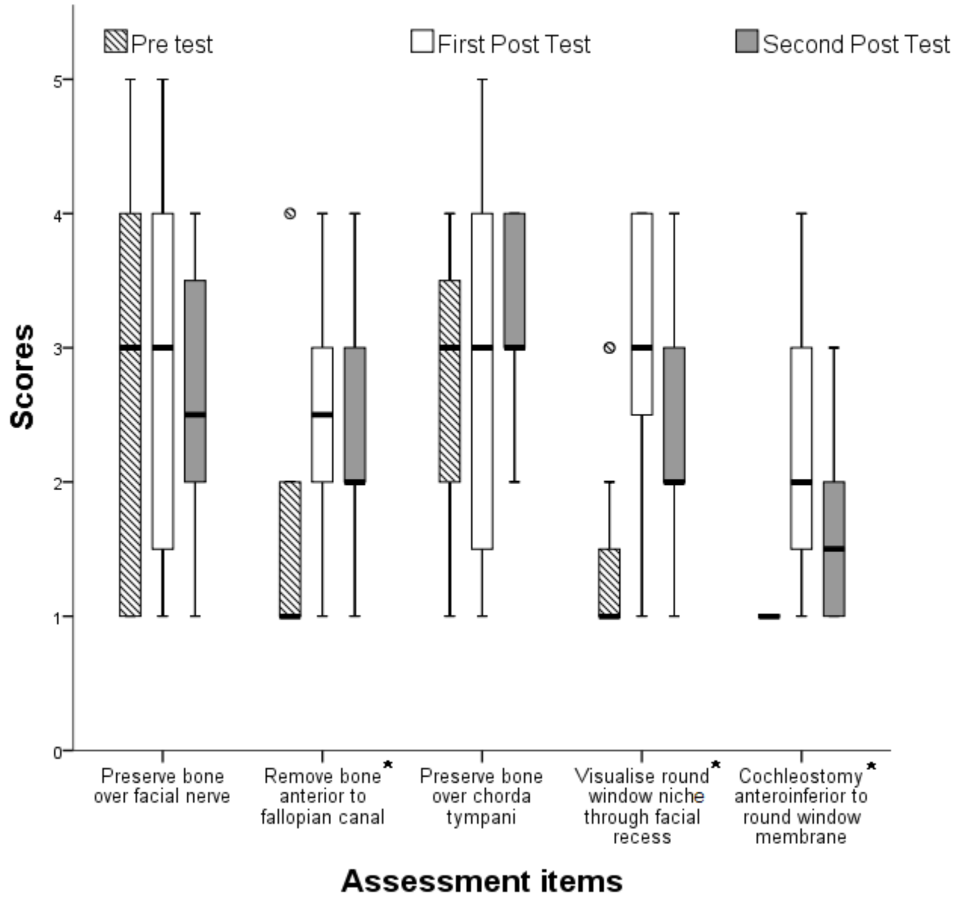

Figure 5: Cochlear implant competency task based checklist assessment items in boxplot showing median and interquartile range, 90th percentile, circle denotes outliers. Significant differences were seen in the performance scores between pre-test to first post-test and pre-test to second post-test as 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. p values included in Table 2.

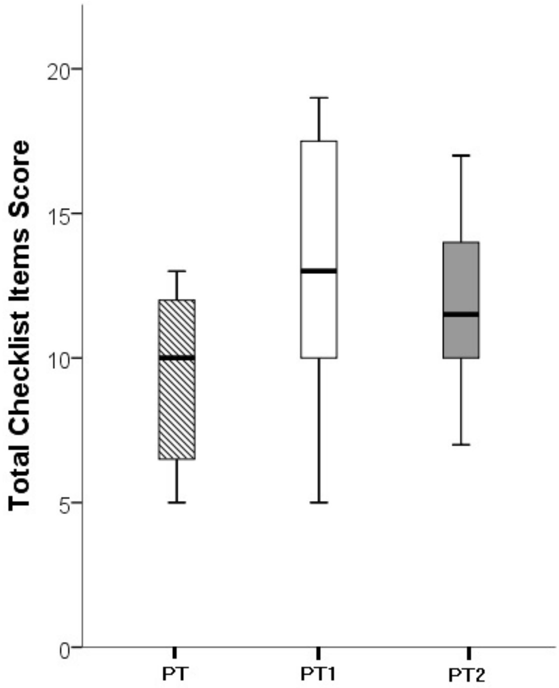

Figure 6: Combined score of cochlear implant competency task based checklist assessment items in boxplot showing median and interquartile range and 90th percentile. PT = pre-test, PT1 = first post-test, PT2=second post-test. A significant difference was seen between the pre-test and both post-tests. p values included in Table 2.

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	
	p value	r value	p value	r value	p value	r 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 visualise 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	**0.007**	**0.782**	**0.005**	**0.816**	0.694	0.113

task based checklist						

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).

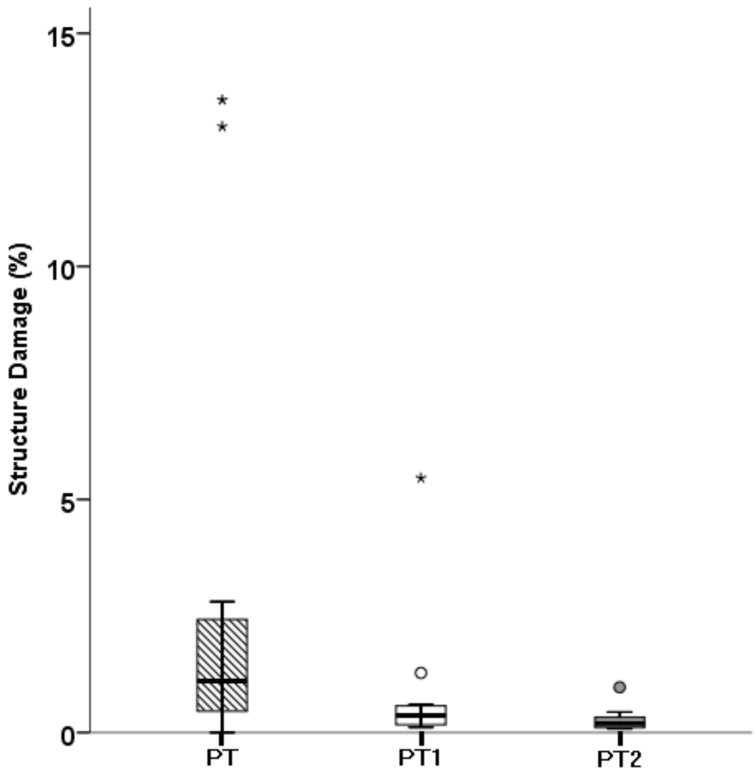

Figure 7: Boxplot showing median and interquartile ranges and 90th percentiles for percentage (%) structural damage. PT=pre-test, PT1= first post-test, PT2 = second post-test. A significant reduction in structural damage was seen between the pre-test and both post-tests.

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; Yi C 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, Avery, Laopaiboon, Kennedy, & O'Leary, 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 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, Chang, Chien, Chung, & Hsu, 2007; Walsh, Ling, Wang, & Carnahan, 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 randomised control trial of 8 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, French, McDaniel, Panchanathan, & Smith, 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, Puttemans, & van Steenberghe, 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 (Laeeq et al., 2009; Zirkle, Taplin, Anthony, & Dubrowski, 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).

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 VR this simulation platform is optimised 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 skeletonising (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, Stredney, Powell, Hittle, & Kerwin, 2016).

In conclusion, this study clearly indicates that there is an improvement in performance of otolaryngology trainees after using a virtual reality 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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Table 1. Combined instruction steps text for advanced temporal bone simulation module

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

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

Figure 2. Flow diagram of study design

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.

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.

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 percentiles 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.