Design and Evaluation of a Virtual Reality Simulation Module for Training Advanced Temporal Bone Surgery

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***Abstract*—Surgical education has traditionally relied on cadaveric dissection and supervised training in the operating theatre. However, both these forms of training have become inefficient due to issues such as scarcity of cadavers and competing priorities taking up surgeons' time. Within this context, computer-based simulations such as virtual reality have gained popularity as supplemental modes of training. Virtual reality simulation offers repeated practice in a risk-free environment where standardised surgical training modules can be developed, along with systems to provide automated guidance and assessment. In this paper, we discuss the design and evaluation of such a training module, specifically aimed at training an advanced temporal bone procedure, namely cochlear implant surgery.**

***Keywords*-Virtual Reality Surgery Simulation, Surgical Training, Automated Guidance in Surgery Simulation**

I. Introduction

The benefits of Virtual Reality (VR) based surgical training are well established: it provides controlled and repeated training opportunities, enables exposure to high-risk or rarely encountered clinical scenarios in a risk-free environment [1], and thus has the potential to reduce training times, increase efficiency within the operating theatre and reduce surgical errors [2]. Previous researchers have demonstrated that skills acquired through VR based training transfer to the real surgical environment and that time spent training in VR can be as effective as time spent on traditional training prior to first-time cadaveric temporal bone drilling [3], [4].

However, the effectiveness of any simulation based education program is mainly dependent on the quality of its curriculum [5]. Thus, the design of a training program or curriculum for VR simulation is equally if not more important than its fidelity (or its suitability to train a given task). When designing a surgical training system, several considerations, such as an understanding of the skill to be trained, how it is trained manually, and how performance is evaluated should be considered [5]. Approaches to surgical curriculum development [6], [7] can be used to aid the design of such simulation based training systems.

Although there have been numerous works that have addressed how more basic temporal bone procedures such as cortical mastoidectomy can be trained using VR simulations [8], [9], [10], those that address more advanced surgeries are scarce. In this paper, we discuss the design and validation of a VR simulation based training module optimised to train an advanced temporal bone surgical procedure: cochlear implant surgery. The novel contributions this paper offers are: 1) details of the design of the simulation module according to concepts of curriculum development and 2) its qualitative validation through a user study.

The rest of the paper is organised as follows. Section II briefly describes the simulation platform and the surgery under consideration. Section III discusses the design and development of the proposed VR simulation module based on concepts of surgical curriculum development. Section IV evaluates the training module through a user study and section V concludes the paper with a discussion of results and future avenues of research.

II. Setting

A. Simulation Platform

For the development of the surgical training module for advanced temporal bone surgery, the University of Melbourne VR temporal bone surgery simulator was used. This simulator was developed by our group and displays a virtual model of a temporal bone constructed from a segmented MicroCT scan of a human cadaver. The bone and associated anatomical structures of interest are rendered separately using polygonal meshes generated using surface rendering techniques. The trainee interacts with the virtual model using a pen-like device that provide haptic or force feedback, and acts as the surgical drill. The hardness of the bone and the relative softness of the anatomical structures, as well as vibrations are experienced through the haptic device during drilling. The illusion of a 3D operating space is created when viewed through 3D glasses by presenting the trainee with two slightly offset projected images. With this simulator, surgeons can practice temporal bone operations to remove

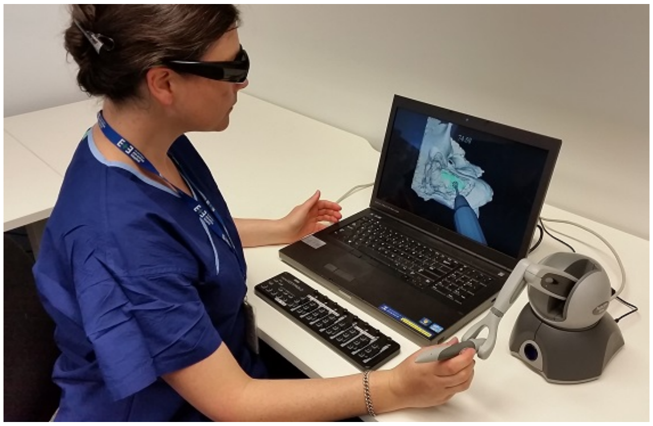


Figure 1: A surgeon performing an operation on the University of Melbourne VR temporal bone surgery simulator.

disease and improve hearing. This often involves removing the temporal bone (cortical mastoidectomy) or operating on the middle or inner ears. Figure 1 shows a surgeon performing an operation on the VR temporal bone surgery simulator.

B. Surgery to be Trained

The operation under consideration is cochlear implant surgery. This is an advanced temporal bone surgical procedure aimed to treat or augment hearing loss. The surgery is performed by drilling the temporal bone to expose the cochlea into which an electrode is placed to transfer sound waves as electrical signals. The drilling requires navigation around sensitive anatomical structures such as the facial nerve (see figure 2), damage to which can cause permanent impairment such as facial paralysis.

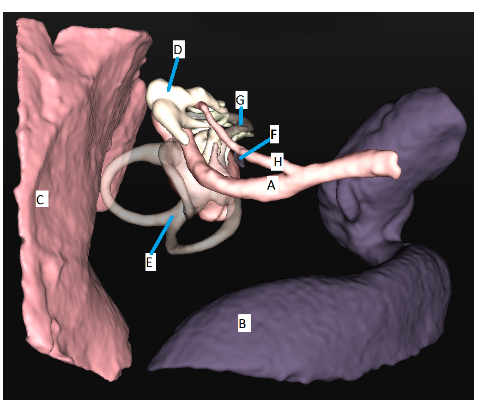


Figure 2: Anatomical structures of the middle and inner ear that have to be navigated in the performance of cochlear implant surgery: A) facial nerve, B) sigmoid sinus, C) dura, D) ossicles, E) semicircular canals, F) round window, G) cochlea, and H) chorda tympani.

The initial step of cochlear implant surgery: preparation of the mastoid (cortical mastoidectomy) is the basic step in many advanced surgeries and is relatively easy to master. Thus, the training module discussed here only considers the later, more advanced parts of the surgery (identifying the facial nerve, skeletonising the facial recess, and drilling the cochleostomy through which the electrode is to be inserted into the cochlea). Thus, temporal bones that were drilled up to cortical mastoidectomy by an expert surgeon were used in the development of this training module.

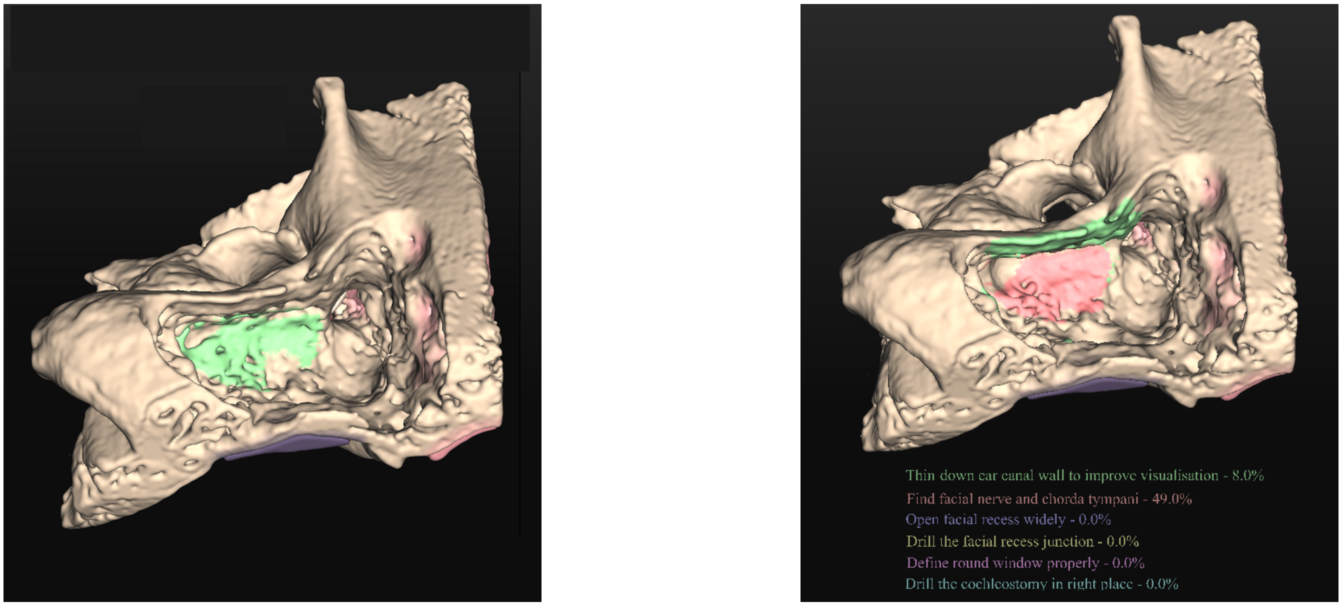
III. Design of the Simulation Module for Training Advanced Ear Surgery

A. Concepts of Surgical Curriculum Development

Stefanidis [5] discusses factors that contribute to the effectiveness of a surgical curriculum. These factors were addressed with respect to the procedure under consideration (cochlear implantation) through discussions with expert surgeons, in the development of the training module.

1) Deliberate Practice and Learner Motivation: Deliberate practice is defined as ‘effortful activities designed to optimize improvement’ [11] and comprises two essential components. First, practice needs to be goal oriented and repeated; repeated performance of specific tasks allows trainees to appreciate variations in the way a single activity is constituted, as well as enabling them to refine their practice to concentrate on specific variations. Second, practice needs to be accompanied by timely and appropriate feedback. To engage in deliberate practice, the learner needs to be motivated internally, externally, or both [5]. In our system, deliberate practice is prompted through repeated practice, goals (or sub-tasks to be completed), and concurrent guidance on how they can be achieved. External learner motivation is promoted in the form of terminal feedback or assessment as compared to the performance of an expert surgeon, the level of which the trainee can aspire to achieve.

2) Performance Feedback: Feedback is essential for effective skill acquisition, and must be both timely and contextually relevant [12], [13]. Its purpose is to reinforce strengths, address weaknesses, and foster improvements in the learner by providing insights into the consequences of their actions and by highlighting the differences between intended and actual results [5]. Concurrent and terminal feedback are two common variations of when to present feedback, the effectiveness of both of which has been established in previous studies [14]. However, in practice, experts would provide both forms of feedback to a trainee. Kahol et al. [15] found in a study of Obstetric and Gynaecology residents, that a combination of concurrent and terminal feedback caused significant performance improvements. In our system, we adopt this model of feedback provision: a combination of concurrent guidance and terminal feedback.



(a) Concurrent guidance in the instruction mode.

(b) Terminal feedback in the practice mode.

Figure 3: Screen shots of the proposed training module.

3) Task Demonstration: Effective instruction allows learners to understand the intricacies of a given task and assists them in forming a mental model for how to accomplish it [5]. Video-based instruction has gained popularity as an effective method of task demonstration in simulation based surgical training [16], [17]. We employ this technique by providing instruction for performing the surgery through a video recorded by an expert surgeon.

4) Practice Distribution: Distributed practice is seen to be superior to massed practice in skill acquisition [18], but the size of this effect appears to be task dependent and influenced by the interval between training sessions (inter-training interval) [19]. Simpler tasks are learned faster, while more complex tasks benefit from a more distributed approach. However, the optimal inter-training interval is task dependent, and should be determined through expert consultation and experimentation. As cochlear implantation is a relatively complex procedure, we tested an inter-training interval of a week with two separate sessions, each of which consisted of training on three different temporal bones.

5) Task Difficulty and Practice Variability: Practice at progressively increasing levels of difficulty has been seen to enhance surgical skill acquisition [20]. In addition, it was also observed that practicing at a medium level of simulation difficulty (when compared to an easy level) significantly improved performance in minimally invasive surgery [21]. Practice variability, or the order in which tasks are undertaken can also have an effect on skill acquisition. However, these effects seem to be dependent on the task and other factors as well [22]. Considering that the task being trained in our application is complex, we use specimens with a medium level of difficulty (rated 3 out of 5, with 5 being the most difficult, by expert surgeons). The order in which the specimens are provided to the trainee is constant, so that each trainee can be offered a uniform program of training.

6) Proficiency Based Training: Proficiency based curricula set training goals that are derived from expert performance and give learners a performance target to achieve [5]. By providing such performance targets and immediate performance feedback to learners via knowledge of results, it promotes deliberate practice, boosts motivation, and enhances skill acquisition [23], [24]. In our system, the procedure is divided into steps and each step is presented as a goal or sub-task. Each sub-task has to be completed before the next sub-task is presented, leading to an interactive and goal oriented learning process. Terminal feedback provides an overall performance overview when compared to that of an expert surgeon. Terminal feedback can be displayed on demand, and the trainee can continue drilling after it has been provided, ensuring that performance objectives are met.

B. Design of the Simulation Tasks

The above concepts were incorporated in to the design of the simulation tasks in the form of two training modes: instruction and practice. Training for one specimen consists of completing both of these modes.

1) Instruction Mode: The trainee is presented with a temporal bone that has been drilled up to a cortical mastoidectomy. Step-by-step guidance is provided on how to perform a cochlear implantation for this specimen. At each step, the areas to be drilled are highlighted and a verbal message instructs the trainee on the rationale and technique.

The steps are identified by manually segmenting a recorded procedure conducted by an expert surgeon on the simulator. The steps are classified into four types: drilling, rotation, magnification, and burr size. The areas drilled, rotation parameters, magnification level, and burr size for each step are obtained from the simulator metrics that are automatically saved at regular intervals by the simulator during a surgery. Visual guidance is provided by highlighting the voxels to be drilled for a drilling step, and through animations for the other types of steps. Verbal explanations are provided using advice recorded by an expert surgeon.

A step is presented only once the previous step has been sufficiently completed (identified using pre-defined threshold values). The presentation of a new step acts as feedback for the completion of the previous step, as well as a mode of guidance on how to perform the current step. Once the procedure is completed, the verbal notification to the fact is presented to the trainee. Figure 3a shows how a drill step is highlighted in the instruction mode.

2) Practice Mode: The trainee is given the opportunity to practice on the same specimen as that of the instruction mode. However, no concurrent feedback is provided in this mode. The trainee can request terminal feedback once they deem the procedure has been completed. When they have evaluated their performance and identified ways of improving the dissection using the terminal feedback, they can continue drilling. This process can be repeated as required.

Terminal feedback is provided by comparing the dissection of the trainee with that of a pre-recorded expert. The temporal bone is divided into the drill steps identified in the instruction mode. Undrilled voxels are highlighted in different colours for each step and textual explanations are also provided, along with a quantitative evaluation of completion. Figure 3b shows how terminal feedback is provided in the practice mode.

C. Structure of the Complete Training Module

Figure 4 shows a flow diagram of the complete training module discussed here. It comprises a video tutorial for task demonstration, training in instruction and practice modes on six temporal bone specimens (three of which are contralateral or mirror images of the other three), spaced into two sessions consisting of three specimens each with an inter-training interval of one week.

IV. Experimental Results

A. Overview of the Study

Twelve otolaryngology surgical residents were recruited to evaluate the training module. After a video tutorial, participants were given time to familiarise themselves with the VR

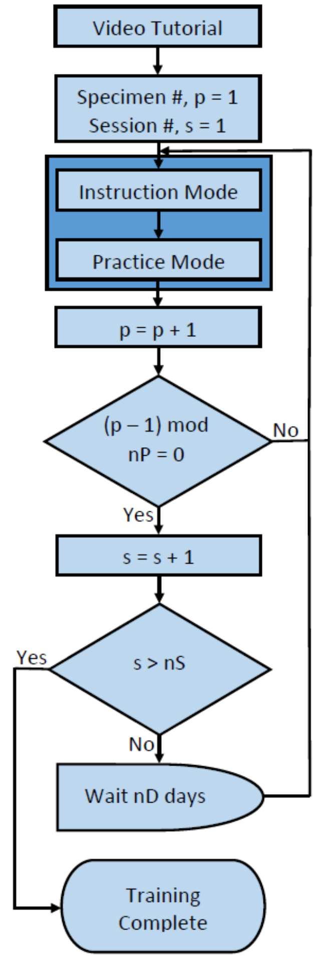


Figure 4: Flow diagram of the training module. nP, nS, and nD are number of specimens per session, number of sessions, and number of days between sessions respectively.

system. They were then asked to perform a cochlear implant surgery on a partially drilled virtual temporal bone, to gauge their initial skill level (pre-test/PT). Next, they underwent training on the simulation tasks described in section III-B with training parameters set to those discussed in section III-C. After the completion of the training, participants were asked to perform the same operation on the mirror image of the temporal bone used in the pre-test (post-test1/PT1). Next, they were given a new temporal bone to perform the procedure on that was not seen in the pre-test or the training (post-test2/PT2). The performances were recorded using video capture software and through the simulator. Details of the study can be found in Copson et al. [25].

B. Evaluation of Effectiveness

To test the effectiveness of the training module, the recorded videos were assessed by an expert surgeon blinded to participant identity and test using a validated performance

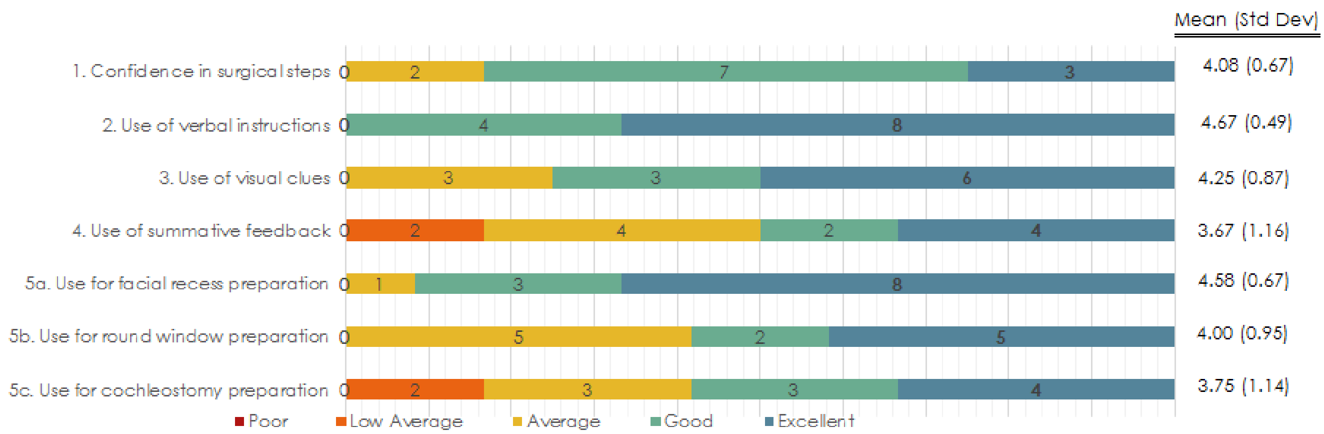


Figure 5: Results of the participant questionnaire for questions 1-5. Colour denotes Likert scale responses.

scale [26]. Amount of damage to structures (relative to the total drilled area) was calculated using metrics saved by the simulator. Wilcoxon signed rank tests showed that there were significant improvements in both post-tests when compared to the pre-test for both overall surgical performance (PT $\rightarrow$ PT1: p=0.007, PT $\rightarrow$ PT2: p=0.005) and structure damage (PT $\rightarrow$ PT1: p=0.023, PT $\rightarrow$ PT2: p=0.01). A detailed analysis of these results can be found in Copson et al. [25].

C. Evaluation of Usability

A participant feedback questionnaire was given to each participant at the end of the study to assess the usefulness of the training module. It consisted of the following questions:

1) After completing this training, how confident do you feel with the surgical steps involved in preparing a temporal bone for cochlear implantation?
2) How useful did you find the verbal instructions?
3) How useful did you find the visual clues?
4) How useful did you find the summative feedback?
5) How useful do you feel this training is specific for:
   a) Facial recess preparation
   b) Round window preparation
   c) Cochleostomy
6) In what stage of training do you envisage this simulator module would be of most benefit?
   a) Before temporal bone laboratory
   b) Concurrent with temporal bone laboratory
   c) During theatre based training
   d) Continued professional development for established surgeon

For question 1-5, a Likert scale was given with scores of 1 to 5 for poor to excellent. For question 6, participants were able to indicate as many options as required.

Figure 5 summarise the results of the Likert scale questions on the participant feedback questionnaire, along with the mean and standard deviations for each question. On average, participants found the concurrent verbal and visual cues more helpful than summative/terminal feedback. The participants found the training more useful for facial recess and round window preparation than cochleostomy preparation. In response to question 6, 75% of the participants felt that the learning module would be suitably timed prior to temporal bone laboratory courses, 58% felt it would be useful concurrent to temporal bone courses, 67% felt that it would be useful concurrent to theatre base training and 25% felt it would be useful as part of continued professional development.

V. Conclusion

We discussed the design and evaluation of a VR module for training an advanced temporal bone procedure, namely, cochlear implant surgery. We showed through a user study of surgical residents, that the proposed system is not only effective in training the surgery, but also highly usable. Although this VR training module was developed for a specific surgery, and as such, some parameters such as practice distribution and task difficulty were tailored accordingly, it could easily be extended to other VR surgical training platforms and other surgical procedures.

Future work include user studies to determine optimal parameter settings for training advanced temporal bone surgeries (e.g., inter-training interval, number of specimens/sessions). Comparison of the effectiveness of the training provided by this simulation module with traditional training methods such as cadaveric dissection is another avenue of future investigation. Clinical studies to evaluate how the skills learned through the simulation module are transferred to the operating theatre as surgeons undertake real operations is also a possible research direction.

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