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Original Article

Developing an Evidence-Based Surgical Curriculum: Learning from a Randomized Controlled Trial of Surgical Rehearsal in Virtual Reality

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BACKGROUND: Surgical rehearsal — patient-specific preoperative surgical practice — can be provided by virtual reality simulation. This study investigated the effect of surgical rehearsal on cortical mastoidectomy performance and procedure duration.

METHODS: University students (n = 40) were randomized evenly into a rehearsal and control group. After watching a video tutorial on cortical mastoidectomy, participants completed the procedure on a virtual reality simulator as a pre-test. Participants completed a further 8 cortical mastoidectomies on the virtual reality simulator as training before drilling two 3-dimensional (3D) printed temporal bones. The rehearsal group received 3D printed bones they had previously operated on in virtual reality, while the control group received 2 new bones. Cortical mastoidectomy was assessed by 3 blinded graders using the Melbourne Mastoidectomy Scale.

RESULTS: There was high interrater reliability between the 3 graders (intraclass correlation coefficient, $r = 0.8533$, $P < .0001$). There was no difference in the mean surgical performance on the two 3D printed bones between the control and rehearsal groups ($P = .2791$). There was no significant difference in the mean procedure duration between the control and rehearsal groups for both 3D printed bones ($P = .8709$). However, there was a significant decrease in procedure duration between the first and second 3D printed bones ($P < .0001$).

CONCLUSION: In this study, patient-specific virtual reality rehearsal provided no additional advantage to cortical mastoidectomy performance by novice operators compared to generic practice on a virtual reality simulator. Further, virtual reality training did not improve cortical mastoidectomy performance on 3D printed bones, highlighting the impact of anatomical diversity and changing operating modalities on the acquisition of new surgical skills.

KEYWORDS: Cortical mastoidectomy, ear surgery, preoperative planning, simulation training, surgical rehearsal, virtual reality

INTRODUCTION

As surgical training programs attempt to modernize to match the changing pressures on healthcare providers, there is a need to consider the efficacy of different training methods to support this transition. Traditionally, surgical training has been based upon the time-intensive apprenticeship model, where surgical trainees are directly supervised by an expert according to the philosophy of "see one, do one, teach one." However, the global reduction in working hours, changes to shift working, and service provision pressures on trainees have limited trainees' ability to gain sufficient operative experience solely by this approach,[1] leading to dissatisfaction amongst trainees.[2] The 2015 Royal College of Surgeons of England report, "Improving Surgical Training," highlighted the need to incorporate simulation into competence-based training curriculums to augment the opportunities for technical skill development.[3]

Otolaryngology is one example of a surgical specialty employing a new competency-based curriculum in the United Kingdom, which encourages the use of simulation to aid trainees' development of "craft skills."[4] Virtual reality (VR) simulators have previously

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proven effective at improving novice performance in cortical mastoidectomy[5,6]; this is a common Otology operation with a number of important indications, including chronic otitis media with or without cholesteatoma, and represents a core competency in Otolaryngology training.[4]

Furthermore, VR simulators can provide a platform for surgical rehearsal: preoperative preparation for an operation through the use of patient-specific simulation.[7-10] This promises to further increase their utility by both allowing trainees, particularly early career trainees, to increase their operative experience; and improving patient safety by helping surgeons prepare for upcoming operations. Although early studies suggest patient-specific rehearsal improves surgeons' confidence,[7,8] high-quality evidence is needed to confirm an objective performance benefit to justify the time and financial costs of introducing it into surgical training programs.

This study reports the findings of a randomized controlled trial designed to test the efficacy of task-specific VR rehearsal versus generic practice on a VR simulator on cortical mastoidectomy performance and procedure duration.

METHODS

Study Recruitment

Participants were University students without any prior operating experience. Participants were allocated to either the rehearsal group (n = 20) or the control group (n = 20) by random permuted block randomization. This study was approved by the Human Research Ethics Committee of the Royal Victorian Eye and Ear Hospital (HREC number: 19/1419HL). All participants provided signed consent.

Virtual Reality Simulator

The University of Melbourne VR Temporal Bone Simulator was the platform used to provide preoperative practice in this study.[11] It provides the user with a 3-dimensional (3D) image of a temporal bone, which they can "feel" and interact with using a haptic arm, that is represented as a virtual drill on the simulator. The simulator can provide 3 types of automated guidance: (i) procedural guidance, where the next step of the operation is highlighted in green; (ii) artificial intelligence generated verbal feedback on drilling technique; and (iii) bone transparency, allowing the user to visualize the internal structures of the temporal bone.[12]

3D Printed Bones

3D volumetric temporal bone models, with segmented internal structures, taken from the VR simulator were prepared for printing using Meshmixer (Autodesk, San Rafael, Calif, USA) and FlashPrint (FlashForge 3D Printer, Jinhua City, China). Polylactic acid (PLA) was selected as the material to print the models, as a previous study showed it to have a similar appearance and physical likeness to human bone.[13] The models were printed in 2 colors using a Flashforge Dreamer 3D printer (FlashForge 3D Printer): white for the bone and pink for anatomical landmarks (dura, sigmoid sinus, facial nerve, and ossicles). When operating on 3D printed temporal bone (PTB) models, study participants were provided with a handheld surgical drill, irrigation, and a surgical microscope.

Cortical Mastoidectomy Training

All temporal bone models were right-sided. Specimens were numbered from 0 to 5, with each number representing a different unique temporal bone anatomy. The names of the specimens are prefixed with virtual temporal bone (VTB) or PTB, describing the modality in which participants encountered the model.

On day 1, participants were shown a 15-minute video on how to perform a cortical mastoidectomy, and then, after familiarization with the simulator, they were asked to perform the procedure as a pre-test (test 0) on the simulator to assess their baseline skill level (VTB0). This was the same temporal bone anatomy used in the tutorial video. Next, participants underwent further training on 2 temporal bone models on the simulator, each with different anatomy (VTB0 and VTB1). This training was composed of 2 procedures on each temporal bone model, 1 with and 1 without automated guidance. Automated guidance was only provided for alternate procedures to prevent individuals from becoming dependent on instruction, which may result in a drop in performance with the removal of the guidance on the 3D printed bones.[5]

On day 2, participants completed another 2 cases on the simulator with and without guidance (VTB2 and VTB3). Then, participants were taken into the laboratory and familiarized with the drill and microscope before being asked to carry out 2 further unguided cortical mastoidectomies on 2 3D printed bones, termed test 1 and test 2. The rehearsal group received temporal bone models with the same anatomy as the virtual models they had just encountered on the simulator (PTB2 and PTB3), while the control group received 2 previously unseen models (PTB4 and PTB5).

All temporal bone models presented to both groups were intended to be of equivalent difficulty. Figure 1 illustrates the sequence of cortical mastoidectomy training participants received.

Temporal Bone Grading

Cortical mastoidectomy performance for the VR pre-test and 2 3D printed bones was assessed independently by 3 blinded graders (2 Consultant Otologists and 1 Otolaryngology researcher) using the recently developed Melbourne Mastoidectomy Scale (MMS), which is a validated 20-item binary end-product score (Appendix A).[14] Figure 2 shows VR and 3D printed versions of the same bone.

Statistical Analysis

Statistical analysis was carried out using MATLAB R2019b (Mathworks, Natick, Mass, USA). Interrater reliability was assessed using the intraclass correlation coefficient (ICC).[15] An analysis of covariance test was used to compare MMS scores between the rehearsal and control groups, adjusting for baseline skill level using the pre-test scores. A one-way analysis of variance was used to compare MMS scores between test 0, test 1, and test 2 for both groups. Procedure length was compared between the rehearsal and control group using unpaired *t*-tests and between test 1 and test 2 using paired *t*-tests. All statistical tests were performed at the level of alpha = 0.05.

RESULTS

A total of 120 procedures, 40 on the VR simulator and 80 on 3D printed bones, were assessed independently by 3 graders. There

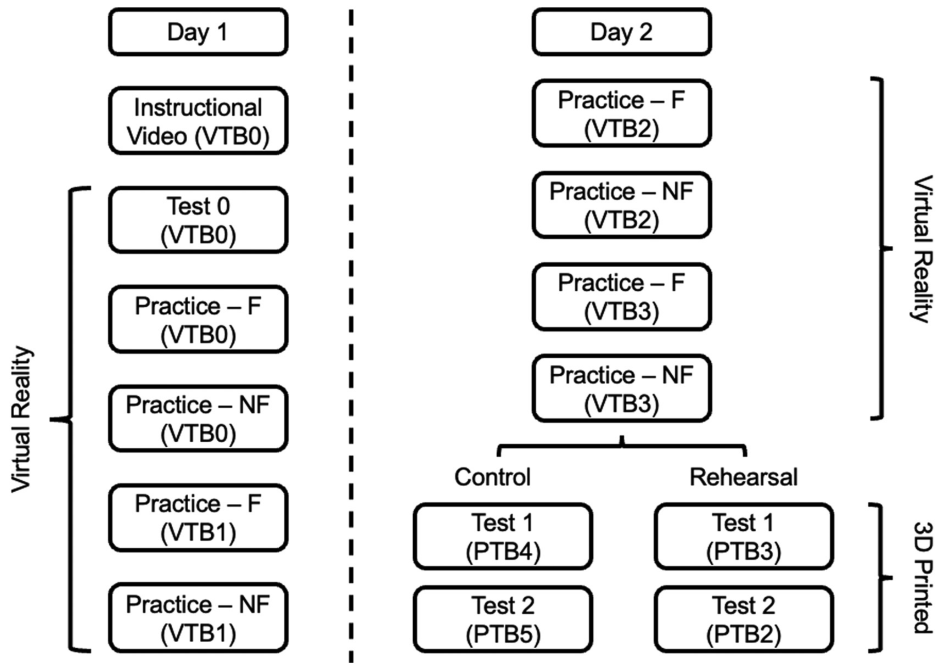

Figure 1. A flow diagram of the cortical mastoidectomy training study participants received over 2 consecutive days. *F, with automated feedback; NF, no automated feedback; PTB, printed temporal bone; VTB – virtual temporal bone.

was high interrater reliability between the 3 graders (ICC coefficient, $r=0.8533$, $P<.0001$).

Melbourne Mastoidectomy Scale scores for the 3 tests are illustrated in Figure 3. Mean ± standard deviation MMS scores for test 0 (VR pre-test) were 10.85 ± 3.65 in the control group and 10.91 ± 3.48 in the rehearsal group; for test 1 (first printed bone), they were 9.77 ± 3.15 in the control group and 8.97 ± 3.54 in the rehearsal group; for test 2 (second printed bone), they were 10.87 ± 3.50 in the control group and 9.80 ± 3.51 in the rehearsal group. There was no difference in the mean surgical performance on the 2 3D printed bones between the control and rehearsal group, as measured with the MMS ($P=.2791$). Additionally, there was no difference in MMS score between the 3 tests (test 0, test 1, and test 2) regardless of the study group ($P=.1429$).

Mean ± standard deviation procedure duration for test 1 was 39.04 ± 15.56 minutes in the control group and 42.10 ± 15.50 minutes in the rehearsal group; for test 2, it was 30.22 ± 11.31 minutes in the control group and 26.08 ± 9.89 minutes in the rehearsal group. There was no significant difference in the mean procedure duration between the control and rehearsal group for both 3D printed bones ($P=.8709$), test 1 ($P=.5368$), or test 2 ($P=.2263$). However, there was a significant decrease in procedure duration between test 1 and test 2, the first and second 3D printed bones, in both the rehearsal and control groups ($P<.0001$; Figure 4).

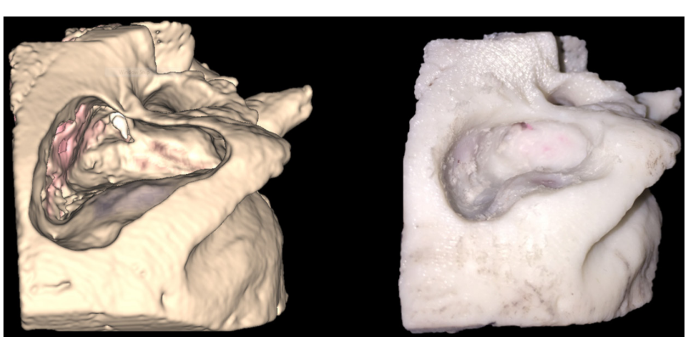

Figure 2. A cortical mastoidectomy was performed on the same temporal bone model on the virtual reality simulator (left) and a 3-dimensional printed model (right).

DISCUSSION

The technical feasibility of VR patient-specific preoperative rehearsal has been demonstrated for cortical mastoidectomy.[7-10] Although, early experiences have been promising,[7-10] its value to surgical performance lacks significant investigation. This randomized controlled trial found task-specific rehearsal to offer no performance benefit to a novice cohort; more importantly, it also found no significant improvement in surgical performance over the period of VR training provided.

Performance Scores

The high interrater reliability between the performance scores assigned by the 3 graders in this study supports the validity of the newly developed MMS for dissections on both VR and 3D PTBs.[14]

There was no difference in cortical mastoidectomy performance between the VR pre-test (test 0) and final surgical performance on 3D PTBs (tests 1 and 2) in both groups, despite the completion of 9 practice procedures on the VR simulator. This contradicts the findings of previous studies on VR temporal bone simulators. One such study showed a significant improvement in cortical mastoidectomy performance following a similar number of VR practice cases in a similar cohort (medical students with no prior surgical experience).[5] However, in this prior study, all procedures were performed on the same VR temporal bone model. Another study found that VR practice improved the performance of Otology Residents in performing the approach to cochlear implant surgery.[16]

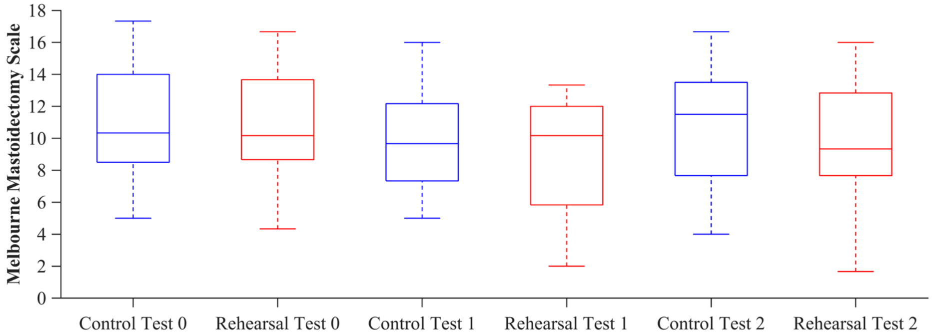

Figure 3. Melbourne Mastoidectomy Scale scores for cortical mastoidectomy procedures by the control and rehearsal groups for test 0 (virtual reality pre-test), test 1 (first printed bone), and test 2 (second printed bone).

One possible explanation of these results is that the novice participants in this study were not able to transfer anatomical and/or procedural knowledge between different specimens. Indeed, it takes surgical trainees a mean of 13 cortical mastoidectomies in the operating theater to achieve competency in the procedure.[17] Learning curves in VR have been shown to be shorter, starting to plateau after only 4 procedures.[5,6] However, these shorter learning curves in VR were based upon repeated procedures on the same temporal bone model; introducing anatomical variation in this study is likely to have prolonged the learning curve.

Retention of the core background anatomical and procedural knowledge after the video tutorial was not tested. Limited task comprehension by the novice cohort may have impaired surgical performance independently of technical skills taught by the VR simulator.

The effect of changing operating modality between VR, 3D printed bones, cadaveric bones, and patients has not been studied and could have had an adverse effect on the performance of our novice cohort. However, several prior studies have shown VR training to improve cadaveric bone dissection suggesting that skills learned in VR are transferable.[18-20]

There was no difference in surgical performance, as measured by the MMS, between the control and rehearsal cohorts. Given the lack of improvement in surgical performance in either group over the course of the study, one must question whether this reflects inadequate task competency in both groups. It is worth noting that this finding is consistent with the only previous randomized controlled trial on surgical rehearsal,[21] which looked at the effect of VR rehearsal prior to neurosurgical aneurysm clippings; its only significant finding was a reduction in the time required to place each clip. The effect of rehearsal has been more extensively studied in endovascular procedures, although the results are mixed: 2 studies reported improved procedure performance[22,23] and 1 reported no difference in any performance metrics between the 2 groups.[24]

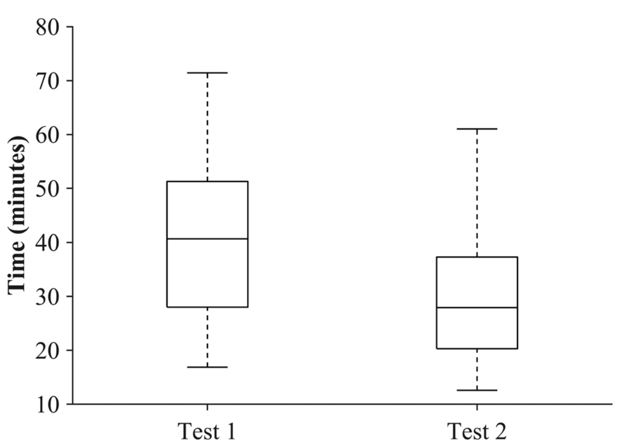

Figure 4. Procedure duration was significantly lower for test 2 (the second 3D printed temporal bone) than test 1 (the first 3D printed temporal bone), $P < .0001$.

Procedure Duration

There was no significant difference in procedure duration between the rehearsal and control groups. This is similar to the findings of the previous studies[21,23,24]; however, 1 previous study on carotid artery stenting did demonstrate significantly shorter procedure durations following patient-specific rehearsal.[22]

There was a significant decrease in procedure duration from test 1 to test 2, demonstrating that regardless of the transfer of surgical skills from VR to 3D printed bones, individuals still need to familiarize themselves with the physical environment and equipment. One notable source of difficulty for study participants was their lack of prior experience using a surgical microscope.

Implications for Study and Curriculum Design

(1) Anatomical variation is essential in VR training modules to adequately prepare trainees for patients' unique anatomy. Our findings suggest anatomical variation substantially prolongs learning curves, which must be accounted for in simulation curricula design.
(2) The effect of training with different operative modalities (VR, 3D printed bones, cadaveric bones, and patients) on learning curves is not adequately understood. Longitudinal data from trainees' surgical logbooks, simulation sessions, and workplace competency assessments could provide valuable insight into this important issue.
(3) There is an efficiency cost when moving between training modalities, such as VR and 3D printed bones, highlighting the need for training with the physical equipment at an early stage for these skills to be applied to the operating theater.
(4) The technical ability to create matched VR and 3D PTBs offers unprecedented opportunities to standardize training and assessment in temporal bone surgery. However, its implementation needs to be carefully informed by evidence.

Limitations

A limitation of this study was the use of 3D PTB models rather than patients or cadaveric specimens. Although the dissection experience using 3D PTBs does not exactly replicate that of real human bone, PLA models have been shown to have a similar appearance and physical likeness to human temporal bones.[13]

Assessing surgical performance on temporal bone models with an end-product dissection score does not necessarily capture all domains of learning. In future studies, it may be beneficial to use a full-procedure assessment tool such as the one developed by Laeeq et al[25] to observe different aspects of performance not accessible when using an end-product score.

Novice participants were recruited to take part in this study as their performance is less affected by previous learning experiences, better reflecting teaching interventions. The mean baseline (test 0) MMS score for this cohort was 10.83, compared to means of 14.4 and 17.3 in cohorts of Otolaryngology registrars and consultants, respectively, who completed the same task in a previous study.[14] This limits the generalizability of the results to more experienced cohorts, where perhaps the information provided by surgical rehearsal would be better appreciated due to a greater contextual understanding of the procedure.

CONCLUSION

In conclusion, this study did not demonstrate an additional advantage to cortical mastoidectomy performance following VR task-specific rehearsal rather than generic practice on a VR simulator for novice operators. Neither did it demonstrate an improvement in cortical mastoidectomy performance after a period of training on a VR simulator, highlighting the impact of anatomical diversity and changing operating modalities on the acquisition of new surgical skills. Although VR offers a promising surgical training modality, empirical evidence is required to optimally integrate it into a new, cost-effective, surgical training curriculum.

Ethics Committee Approval: This study was approved by the Human Research Ethics Committee of the Royal Victorian Eye and Ear Hospital (HREC number: 19/1419HL). All participants provided signed consent.

Informed Consent: Written informed conset was obtained from the participant who participated in the study. All participants provided signed informed consent to participate in this study.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – S.O.L., J.-M.G., S.W.; Design – S.O.L., S.W.; Supervision – S.O.L., S.W., A.C.; Data Collection and/or Processing – B.J.T., J.L., S.W., A.C., A.M.M.-I.; Analysis and/or Interpretation – B.J.T, S.W., S.O.L.; Literature Review – B.J.T.; Writing Manuscript – B.J.T.; Critical Review – S.O.L., J.-M.G., S.W., A.C., A.M.M.-I., J.L.

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Appendix A. The Melbourne Mastoidectomy Scale.

MacEwans Triangle defined as	**Definition**	**Disagree**	**Agree**
1. Temporal line	Cortex removed along the temporal line, delineating the superior limit of dissection.	0	1
2. Posterior external auditory canal wall	Cortex removed behind the posterior wall of the external auditory canal, defining the anterior limit of dissection.	0	1
3. Sigmoid sinus	Cortex removed over the suspected course of the sigmoid sinus, from the temporal line toward the mastoid tip, defining the posterior limit of dissection.	0	1
Middle fossa plate			
4. Identified	Partial exposure/clear identification of the middle fossa plate.	0	1
5. Adequately exposed[4]	Skeletonized middle fossa plate from sinodural angle to tegmen tympani without overhanging cortex.	0	1
6. Identified without minor damage[4]	No small holes in the middle fossa plate.	0	1
7. Identified without major damage[4,†]	No large holes in the middle fossa plate or drilling of the underlying dura.	0	1
Sigmoid sinus			
8. Identified	Partial exposure/clear identification of the sigmoid sinus.	0	1
9. Adequately exposed[8]	Skeletonized sigmoid sinus from sinodural angle towards mastoid tip, without overhanging cortex.	0	1
10. Identified without damage[8,†]	No holes in the overlying bone or direct drilling of the sigmoid sinus.	0	1
11. Sinodural angle defined[8]	Sharp angle between the exposed sigmoid sinus and middle fossa plate.	0	1
External auditory canal			
12. Canal wall preserved	Grossly skeletonized external canal wall.	0	1
13. Posterior canal wall adequately thinned[12]	Precisely skeletonized external canal wall on at least 130 degrees.	0	1
14. Canal wall thinned with no holes[13]	No holes in the external canal wall.	0	1
Mastoid antrum			
15. Antrum opened	Drilling to open the mastoid antrum with exposure of lateral semi-circular canal.	0	1
16. Antrum opened with no damage of the semicircular canals[15,†]	All the semicircular canals remain intact, with no holes.	0	1
17. Incus identified	The entire superior edge of short process of the incus is visible.	0	1
18. Incus identified without damage[17]	No drilling or disruption of the ossicular chain.	0	1
Facial nerve			
19. Vertical section identified	The vertical section of the facial nerve is visible.	0	1
20. Identified with no damage[19,†]	No exposure of facial nerve sheath.	0	1
TOTAL SCORE		**/20**	

Superscripted numbers ([1-20]) represent the dependency of that item on a previous item on the scale denoted by the number.
[†]These items represent major complications of the procedure, and damage of the marked structures can class the dissection as unacceptable regardless of the overall score.