Full citation: Andersen SAW, Varadarajan VV, Moberly AC, Hittle B, Powell KA, Wiet GJ. Patient-specific Virtual Temporal Bone Simulation Based on Clinical Cone-beam Computed Tomography. Laryngoscope. 2021 Aug;131(8):1855-1862.
DOI: 10.1002/lary.29542

Patient-specific virtual temporal bone simulation based on clinical cone-beam computed tomography

Authors:
Steven Arild Wuyts Andersen, MD, PhD (1,2,3); Varun V. Varadarajan MD (1,2); Aaron C. Moberly, MD (2); Bradley Hittle, BSc (4); Kimerly A. Powell, PhD (4); Gregory J. Wiet, MD, FACS, FAAP (1,2)

Affiliations:
1. Dept. of Otolaryngology, Nationwide Children's Hospital, Columbus, OH, USA.
2. Dept. of Otolaryngology–Head and Neck Surgery, the Ohio State University, Columbus, OH, USA.
3. Dept. of Otorhinolaryngology–Head & Neck Surgery, Rigshospitalet, Copenhagen, Denmark.
4. Dept. of Biomedical Informatics, the Ohio State University, Columbus, OH, USA.

Running title: Evaluation of patient-specific simulation

Correspondence: Steven Andersen, MD, PhD. Department of Otorhinolaryngology—Head & Neck Surgery, Rigshospitalet, Blegdamsvej 9, DK-2100 Copenhagen, Denmark. Phone: +45 35452074. E-mail: stevenarild@gmail.com.

Conflicts of interests: None.

Funding: This research was supported by Nationwide Children's Hospital Research Institute Intramural funds and Dr. Andersen by the Independent Research Fund Denmark (8026-00003B).

Financial disclosures: Dr. Moberly has the following disclosures: Research grant support for an unrelated investigator-initiated study of adult aural rehabilitation from Cochlear Americas; paid consultancy for Cochlear Americas, Advanced Bionics; and Investor, CMO, and on Board of Directors for Otologic Technologies. The remaining authors have no financial disclosures.

Meeting information: This work has been accepted for poster presentation at the Triological Society Combined Section Meeting, Orlando, Florida, January 28–30, 2021.

ABSTRACT

Objectives: Patient-specific surgical simulation allows pre-surgical planning through three-dimensional (3D) visualization and virtual rehearsal. Virtual reality simulation for otologic surgery can be based on high-resolution cone-beam computed tomography (CBCT). This study aimed to evaluate clinicians' experience with patient-specific simulation of mastoid surgery.

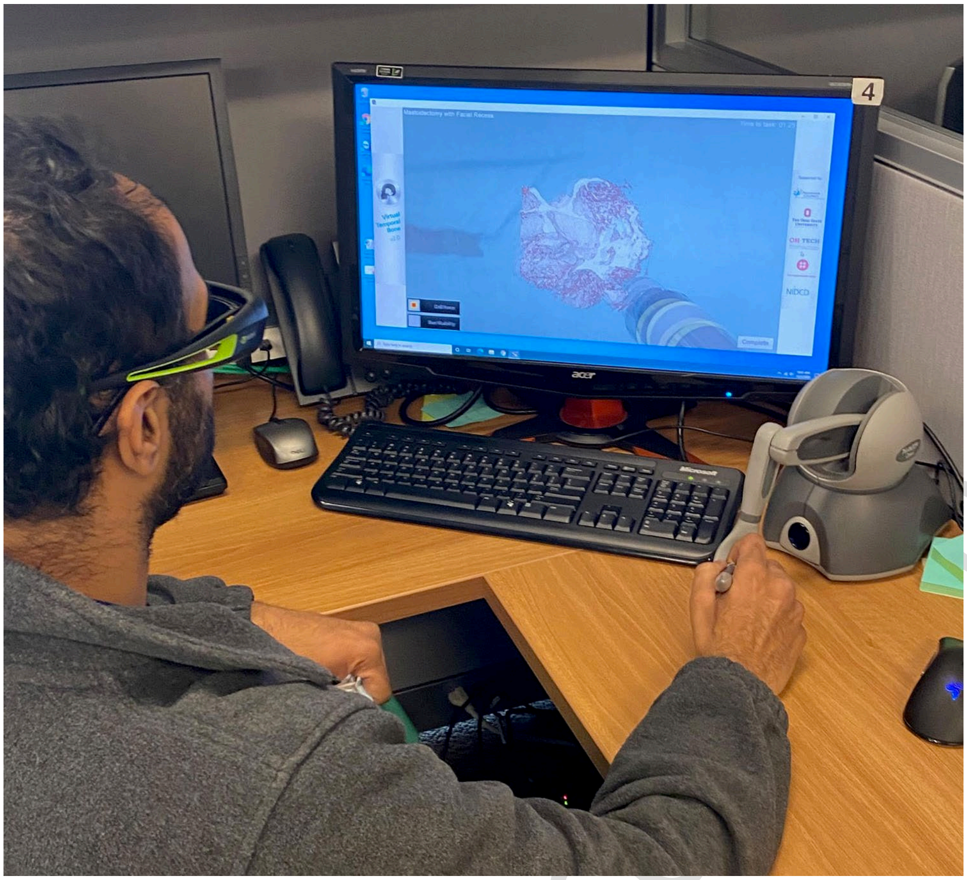
Methods: Prospective, multi-institutional study. Pre-operative temporal bone CBCT scans of patients undergoing cochlear implantation (CI) were retrospectively obtained. Automated processing and segmentation routines were used. Otologic surgeons performed a complete mastoidectomy with facial recess approach on the patient-specific virtual cases in the institution's temporal bone simulator. Participants completed surveys regarding the perceived accuracy and utility of the simulation.

Results: 22 clinical CBCTs were obtained. 4 attending otologic surgeons and 5 otolaryngology trainees enrolled in the study. The mean number of simulations completed by each participant was 16.5 (range 3–22). "Overall experience" and "usefulness for pre-surgical planning" were rated as "good", "very good" or "excellent" in 84.6% and 71.6% of the simulations, respectively. In 10.7% of simulations, the surgeon reported to have gained a significantly greater understanding of the patient's anatomy compared to standard imaging. Participants were able to better appreciate subtle anatomic findings after using the simulator for 60.4% of cases. Variable CBCT acquisition quality was the most reported limitation.

Conclusion: Patient-specific simulation using pre-operative CBCT is feasible and may provide valuable insights prior to otologic surgery. Establishing a CBCT acquisition protocol that allows for consistent segmentation will be essential for reliable surgical simulation.

Key words: temporal bone anatomy; segmentation; virtual reality surgical simulation; patient-specific rehearsal; pre-surgical planning; otology.

Level of Evidence: 3.



INTRODUCTION

Since its infancy in the early 2000s, virtual reality (VR) simulation of temporal bone surgery has been a major leap for otologic surgical training as cadaveric dissection opportunities have become less available at many institutions.[1] Several VR simulators have been developed [2–7]; collectively, evidence supports their efficacy in the training of novices in mastoidectomy.[8] Another recent training modality—three dimensional (3D) printed physical temporal bone models—awaits rigorous educational evidence [9]. Both VR simulation and 3D printing have the exciting potential to be used for basic skills training as well as clinically for patient-specific pre-surgical rehearsal and planning [10]. The idea of patient-specific simulation is to reconstruct the patient's individual anatomy either in virtual space or as a physical replica.[11] This differentiates itself from the common use of simulation for training, where the simulation is designed with an educational purpose to represent standard cases for training. The user experience is generally of a higher level and the mindset is more focused on iterating technique to improve patient specific outcomes rather than learning anatomy and basic surgical techniques. Patient-specific simulation can in contrast to traditional two-dimensional (2D) review of the patient's imaging, allow the surgeon to visualize the patient's temporal bone anatomy in 3D, fully interact with the model for example through virtual drilling, to measure relevant parameters for the surgical intervention, and potentially gain input for selecting the optimal cochlear implant electrode. Altogether, this individual tailoring of the surgery ahead of time could potentially reduce operative time, complications and improve surgical outcomes.[11]

For the patient-specific simulation model to be useful for surgical rehearsal and pre-operative planning, such as for cochlear implant (CI) surgery, the model must precisely replicate the patient's anatomy and any anatomic variants, including minute details such as facial nerve course, facial recess dimensions, degree of temporal bone pneumatization, and round window orientation. High-quality models for temporal bone simulation training have traditionally been based on high-resolution imaging of cadaveric specimens and manual/semi-manual processing to delineate key anatomy such as the facial nerve, chorda tympani, and lateral semi-circular canal.[12] In contrast, patient-specific simulation requires the simulation to be 1) based on clinical imaging with a limited radiation dose, resulting in lower signal-to-noise ratio and resolution, and 2) clinically feasible and therefore dependent on automated processing routines to limit time-consuming manual processes and surgeon involvement in the generation of the model. Altogether, for patient-specific simulation to be useful, the surgeon or trainee must derive benefit from the simulation with regards to perceiving the rehearsal as realistic (e.g. providing visual and tactile cues) and the simulated anatomy needs to accurately correlate with the patient's actual surgical anatomy.

Current systems for patient-specific VR simulation in temporal bone surgery are reported to require considerable time for manual data preparation and processing and have only used clinical imaging of cadaveric temporal bones.[13–15] We have recently developed a pipeline with minimal manual interaction for processing of clinical cone-beam computed tomography (CBCT) for patient-specific simulation. In this study, we imported automatically processed patient scans into our VR simulator with the aim to evaluate clinicians' experiences using patient-specific simulation of mastoid surgery. The purpose was to demonstrate current utility and clinical practicality of the system for patient-specific VR simulation in CI surgery as well as to reveal areas for further improvement based on clinicians' perceptions and ratings.

MATERIAL AND METHODS

Study design

Prospective, multi-institutional study evaluating clinicians' experiences with VR temporal bone simulation of patient-specific models based on clinical CBCT images. Simulations were designed for rehearsal and planning of CI surgery.

Participants and setting

Attending neurotologists and otolaryngology trainees from three academic institutions (Dept. of Otolaryngology at the Ohio State University, Columbus, OH; Dept. of Otolaryngology at Nationwide Children's Hospital, Columbus, OH; and Dept. of Otorhinolaryngology at

Rigshospitalet, Copenhagen, Denmark) were recruited to participate in the study. Participation was voluntary and was not compensated. The study took place from May 2020 to July 2020.

Imaging data

A sample of 22 pre-operative temporal bone CBCTs scans were obtained from adult patients who had undergone CI surgery at the Ohio State University within three years prior to the study. Patients with normal anatomy were included and patients with previous mastoid surgery or congenital temporal bone malformations were excluded. The imaging datasets were stripped from personal health information (PHI) information and research encoded before they were used for this study. The scans were all performed on a clinical CBCT scanner (3D Accuitomo 170, J. Morita Tokyo Mfg. Corp., Japan) and the datasets were extracted from the scanner at the original isotropic resolution of 0.08x0.08x0.08 mm.

Simulation system and data processing

The Ohio State University Temporal Bone (OSU-TB) simulator (Figure 1) is an established VR simulator for temporal bone surgical training, which is disseminated within a consortium of 13 participating institutions.[2] The simulator software runs on a PC with a high-end graphics card (Nvidia Quadro, Nvidia, Santa Clara, CA) and features 3D stereovision using the Nvidia 3D Vision kit and drilling with force feedback using the Geomagic Touch (3D systems, Rock Hill, SC) haptic device. The simulator has several built-in high-quality temporal bone models based on micro-CT datasets (0.1x0.1x0.1 mm resolution) for training of temporal bone surgical procedures such as mastoidectomy and facial recess approach. Recently, we have been developing the simulator to be used for visualization of CBCT imaging datasets allowing for patient-specific temporal bone simulation. This includes integrating a processing pipeline of CBCT datasets with automated segmentation of key anatomical landmarks after manual selection of the incudo-malleolar joint using an atlas-based approach[16] for accurate representation of these structures in the simulation. The bone-covered soft tissue structures that were segmented for visualization purposes (i.e. surgical landmarks) for this study were the facial nerve, chorda tympani, and the lateral semi-circular canal.

Data collection

Participants completed a demographics questionnaire on real-life surgical and simulation experience and were introduced to the simulator controls. We asked participating otologic surgeons to complete as many of the 22 cases as possible within the study period. Each surgeon was assigned a distinct order of cases to ensure that all cases were evaluated. For each patient-specific case, participants were asked to perform a complete mastoidectomy, facial recess, and round window approach in the OSU-TB simulator to emulate the steps of cochlear implantation. We did not set a time limit for completion of the procedure and since the segmentation was performed using the automated algorithms, participants were not involved in the segmentation. Immediately after each case, participants completed a questionnaire on the accuracy and utility of the simulation for that specific case (Appendix 1). This included questions relating to the simulator and simulation experience such as ease of use, reality of experience, model, segmentation, graphics and feel of the drill and the overall usefulness for pre-surgical planning (rated on a 5-point Likert scale: 1 = poor, 2 = fair, 3 = good, 4 = very good, 5 = excellent); impact on determining subtleties of specific patient anatomy (no change, some subtle findings, significantly greater understanding); insights above that of standard imaging (free text); and impact on trainees learning these procedures (no perceived impact, perceived impact on resident trainee, perceived impact on advanced trainee).

Sample-size and statistics

The sample-size was one of convenience deemed sufficient to evaluate the system in relation to representation of patient-specific temporal bone anatomy and experience from users with different levels of training (physicians in practice, fellow and resident trainees). Data were analyzed using SPSS version 26 (IBM, Armonk, NY, USA) for Mac OSX. Descriptive statistics were used to analyze background demographics and questionnaire responses.

Ethics

The study was approved by the Ohio State University Institutional Review Board (#2017B0431). Written informed consent was obtained from participants.

RESULTS

Four attending neurotologists, three otology/neurotology fellows and two otolaryngology residents were enrolled. Background demographics and prior experience is summarized in Table 1. The average number of simulations completed by each participant was 16.5 (range 3–22); each patient-specific simulation case was evaluated by at least 6 participants, and a total of 149 simulations were evaluated.

Participants rated the overall experience of patient-specific simulation as “good”, “very good” or “excellent” in 84.6 % of the simulations (Table 2). The usefulness of the system for pre-surgical planning was also appraised highly with 71.6 % of the simulations being rated “good”, “very good” or “excellent”. In the majority of the simulations, the participant reported a positive impact on determining the subtleties of specific patient anatomy. In 10.7 % of simulations, the participants reported to have gained a significantly greater understanding of the patient’s anatomy compared to standard imaging; in 60.4 % of simulations, the participants reported that they were able to better appreciate subtle anatomic findings after using the simulator. Finally, the participants found that the patient-specific simulation would have a significant impact on trainees learning these procedures especially for resident trainees (44.5 % of simulations) in addition to more advanced trainees (fellows) (37.7 % of simulations). Overall, the ease of use of the system and the segmentation were rated favorably (mean 3.4 and 3.1 points, respectively) whereas the feel of the drill was rated less favorably (mean 2.7 points) (Table 3). Ratings did not display a systematic change with the number of cases completed, suggesting that familiarization with the simulator (i.e. the learning curve) did not affect participant’s perceptions of the simulation. Also, we found no differences in scoring between the different levels of the participants, for example the overall experience was rated at a mean of 3.2 by residents, 3.3 by fellows, and 3.1 by faculty.

We also analyzed if there were case-specific differences in responses (Table 3) by looking at which cases were mostly evaluated above or below the 95 % confidence interval of the mean ratings for each question: four cases were found to be rated mostly very high on the different aspects (case 6, 8, 10 and 20) and four cases were mostly rated very low (case 7, 9, 13, and 17). An example of a highly and poorly rated case is presented in Figure 2. The free text comments indicated that the cases rated highly were the ones that provided valuable insights into variations of the anatomy such as poor aeration or a particularly narrow or wide facial recess. The more poorly rated cases were those with very limited cortical bone, making orientation difficult and drilling limited, as well as having no bone covering the facial nerve and chorda tympani because the scan acquisition field-of-view did not include bone lateral to these structures. Other comments across the cases were that the stapes and round window membrane were not visible. This not surprising since these structures are often poorly visualized on CBCT and therefore not well-defined in the simulation using the current processing pipeline. In general, the limitations of the CBCT acquisition seemed to be the major limitation for good patient-specific simulation. There were only very few reports of technical issues such as the drill stalling or slowing down due to computer processing overload.

DISCUSSION

In this study, we explored clinicians' experience with patient-specific temporal bone surgical simulation based on clinical CBCT using an automated processing pipeline for export to an established virtual reality temporal bone surgical simulator. Overall, we found that clinicians rated the patient-specific VR simulation highly for the overall experience and usefulness for pre-surgical planning. This is consistent with previous studies found in the literature, which report favorably on clinician experience with patient-specific simulation using other VR temporal bone simulation systems.[13–15] Two of these studies report an increase in self-reported confidence [13,14] and all studies find the systems were useful for pre-operative planning and especially training purposes. Our participants also reported that >80 % of the simulations could likely have benefitted surgical trainees. In a recent study, patient-specific simulation was found to be accurate for evaluating round window exposure compared with intraoperative findings,[17] corroborating the potential value of patient-specific simulation.

One of the main challenges in achieving useful patient-specific simulation is accurate segmentation and realistic visualization of anatomical structures, which are key surgical landmarks during temporal bone drilling. This processing often requires some degree of manual interaction and can be time consuming, and therefore we developed automated routines with minimal user interaction in the data preparation and processing for patient-specific VR temporal bone models.[18] Although we asked participants to primarily evaluate the overall realism of the simulation rather than to rate the visualization of individual structures, the stapes and round window membrane was consistently brought up as poorly visualized but important structures. These are typically difficult to distinguish based on thresholding and future efforts should be made to improve our atlas-based approach to segment these for visualization in the VR simulation. Arora et al. asked participating surgeons to rate the adequacy in relation to the visualization of anatomical structures; unsurprisingly, soft tissue structures such as the facial nerve and lateral semi-circular canal were rated less satisfactory.[13] In contrast, we found that the facial nerve and chorda tympani in many cases was pointed out as being very well segmented and providing the clinician with valuable information above that of standard imaging.

One of the main additions to current knowledge of our study is that we used actual patient imaging datasets, whereas the other studies have used imaging of cadaveric temporal bones in a controlled setting. Consequently, we also found that some clinically obtained scans (14 out of 36) were suboptimal or not suited for patient-specific simulation due to blurring or motion artifacts, or the complete inner ear not being included. In other words, a number of scans were a priori insufficient even for assessment by the clinician. Further, of those 22 scans that were suited for automated processing and included in our study, the scan acquisition parameters such as a narrow field of view without the entire cortical mastoid bone was frequently brought up by the clinicians' as making navigation difficult and limiting usefulness for patient-specific simulation. It is therefore important for routine clinical use of patient-specific simulation, that the CBCT acquisition protocol has a slightly larger field of view—optimally from the internal auditory canal to the surface of the mastoid. The CT technician would also need to check the quality of the scan to ensure that extensive motion artefacts are not present.

All our clinicians were able to use the VR simulator independently after a brief introduction to the system, including how to load the different cases, controls and navigation, the 3D glasses, and the haptic device for interactive drilling. In a few instances, the participant experienced technical issues such as the drill stalling, which can be resolved by going into the drill change menu and selecting another burr, or restarting the software. However, the realism of the drill (i.e. the haptics and force-feedback) was overall rated lower than other aspects of the simulation. This can have most likely be explained by the haptic device responding and feeling different than the real-life otosurgical drill as also found in a previous study.[19] Regardless, the haptic experience is an important aspect of temporal bone surgical simulation and can be related to both the software programming and the capabilities of the haptic device itself.[20] Cheaper, commercially available haptic devices can provide less force feedback and have limited degrees of freedom compared with more expensive devices and therefore a less accurate translation of physical forces in the human-interface interaction. Patient-specific VR simulation for use in a clinical setting needs to balance precision and accuracy with feasibility in relation to hardware and software demands as well as cost.

Limitations of our study includes a small number of surgeons. We tried mitigating this by having each surgeon evaluate multiple different cases, having representation from multiple institutions, and participants with different levels of experience. Next, there is an inherent subjectivity in the evaluation using questionnaires and because participants were 1) recruited from our own departments where simulation is implemented for training and 2) volunteered for the study, they could potentially be biased, favoring the simulation more than the average clinician with limited simulation experience. Finally, we used retrospective and de-identified datasets and we did not aim to evaluate impact of patient-specific simulation on actual surgical performance or since we did not directly compare simulation with real-life observations, we cannot determine whether intra-operative findings correspond with the representation in the simulation. In other words, the evaluation of usefulness of the system is limited to participants' perceived impressions. A strength of our study is the use of actual clinical imaging datasets from real patients even though the scan were used after the patient had undergone surgery: this included natural variability in both normal anatomy but also scan acquisition quality, providing us insights into what it takes for patient-specific VR simulation to be useful for future use of the system pre-operatively. A strength to our methodology is the use of automated segmentation based on an atlas approach, which requires no manual interaction in processing except for selection the incudo-malleolar joint.

Altogether, our study suggests several implications and future directions for improving the patient-specific VR simulation. The automated processing seemed to produce appropriate segmentation of the included anatomical soft structures and adequate visualization in the VR simulation environment. The system was found to be user friendly with only few technical glitches but the haptic interaction needs further refinement. Clinical CBCT can be used as a data source, allowing patient-specific simulation. However, clinical implementation and use for prospective patient-specific simulation, i.e. for pre-surgical rehearsal and planning, requires scan acquisition parameters to be optimized for the simulation purpose, which includes increasing field of view and quality control at the time of acquisition. An important future research direction relates to cases of abnormal temporal bone anatomy such as middle ear, mastoid, and cochleovestibular malformations: the value of patient-specific simulation in such cases is most likely higher than for cases of normal anatomy, but methods for reliable automated segmentation need to be developed and validated first.

CONCLUSION

Patient-specific VR simulation of temporal bone surgery based on pre-operative clinical CBCT is feasible. The simulation can potentially provide valuable insights to the surgeon prior to surgery beyond that of standard imaging review. However, an improved CBCT acquisition protocol is essential to ensure that the imaging data can reliably be used for routine pre-surgical rehearsal and planning. Future research should aim to establish reliable patient-specific simulation in cases of abnormal anatomy such as cochleovestibular malformations, which are prevalent in patients with congenital hearing loss.

Acknowledgements: We would like to thank the participating surgeons at the Ohio State University, Nationwide Children's Hospital, and Rigshospitalet; Dr. Alex Farag, the Ohio State

University, for his assistance in obtaining and de-identifying the CBCT scans; and Janet Corbi, Nationwide Children's Hospital, for administrative assistance.

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FIGURE LEGENDS

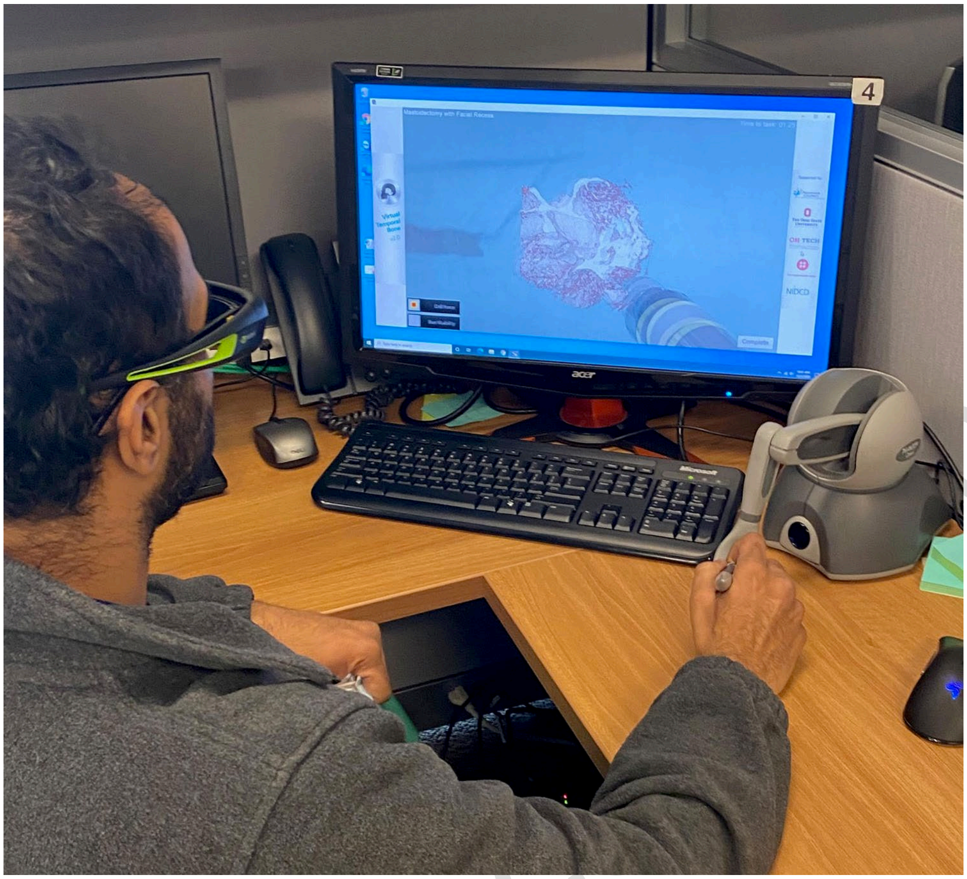

Figure 1. Simulation setup. Surgeon drilling a case on the virtual reality simulator. 3D stereovision is achieved using the Nvidia 3D Vision kit (glasses) and drilling with force feedback using the Geomagic Touch (3D systems, Rock Hill, SC) haptic device.

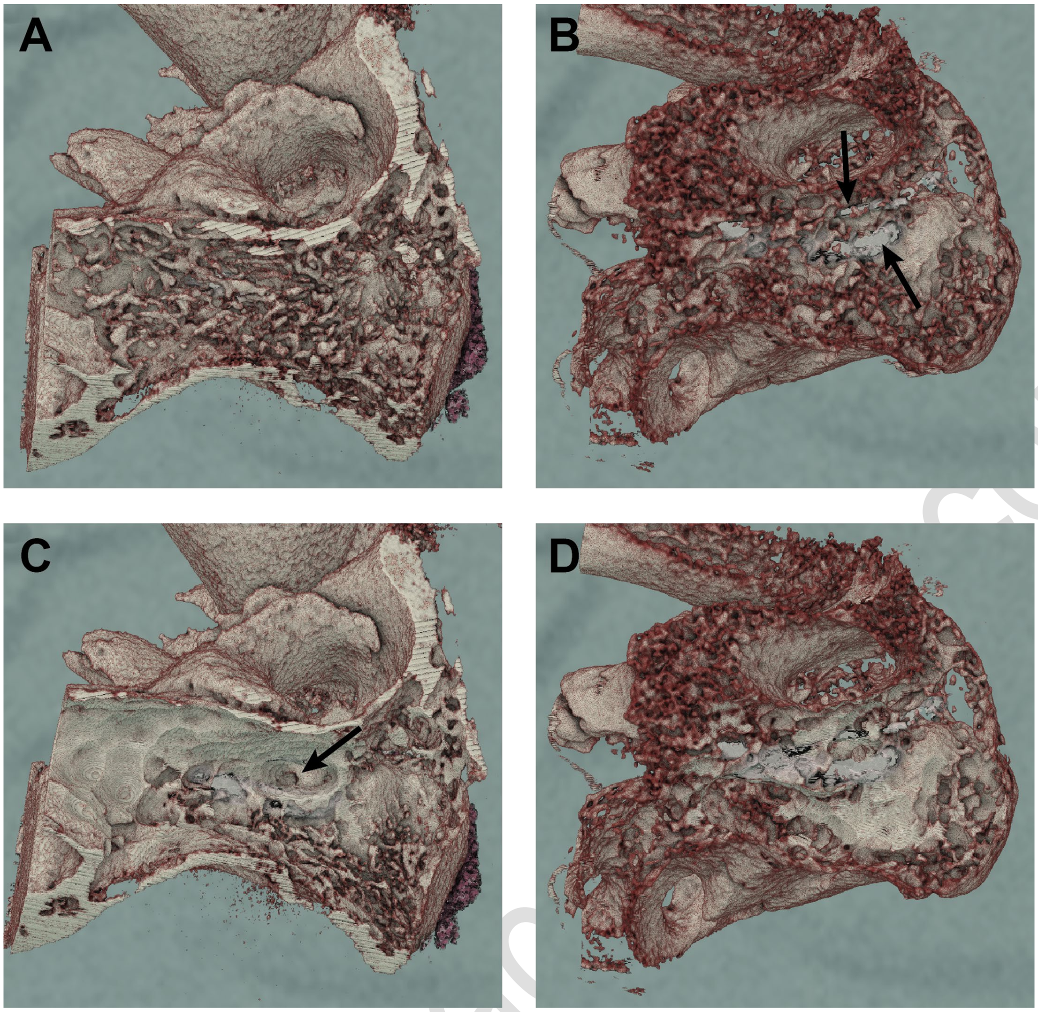

Figure 2. Examples of patient-specific cases in the VR simulator based on clinical CBCT. Top: A case (#6) rated highly by participants across the different aspects evaluated before (A) and after drilling (B) - this case has most of the cortical bone included on the scan and a well-defined facial recess and round window niche (arrow). Facial nerve, chorda tympani, and lateral semi-circular canal segments for this case without the bone volume (C). Bottom: A case (#13) with lower ratings before (D) and after drilling (E) – this case has limited cortical bone included on the scan, making the facial nerve and chorda visible even before drilling (arrows). Facial nerve, chorda tympani, and lateral semi-circular canal segments for this case without the bone volume (F).

APPENDIX LEGEND

Appendix 1. Case questionnaire.

Pre-Surgical Simulation Rehearsal for Temporal Bone Surgery

Case number	
Surgeon ID	

Please rate the following items	1 Poor	2 Fair	3 Good	4 Very good	5 Excellent
Overall experience					
Ease of use					
Reality of experience					
Reality of model, size/orientation					
Reality of segmentations					
Reality of graphics					
Reality of feel of drill					
Sense of immersion					
Overall usefulness for pre-surgical planning					

Impact on determining subtleties of specific patient anatomy

- ☐ No change in perception of patient specific anatomy.
- ☐ Some subtle findings better appreciated after use of system.
- ☐ Significantly greater understanding of patient's anatomy compared to standard imaging and pre-surgical plan.

Insights above that of standard imaging
If new insights were appreciated after PSR on system, please cite them here:

Potential for impact on trainees learning these procedures

- ☐ No perceived impact on trainees over standard pre-surgical planning.
- ☐ Significant perceived impact on resident trainee development of surgical plan.
- ☐ Significant impact on advanced trainee (fellow) for pre-surgical plan.