# Development and evaluation of an immersive virtual reality system for medical imaging of the ear

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## ABSTRACT

Immersive, stereoscopic displays may be instrumental to better interpreting 3-dimensional (3D) data. Furthermore, the advent of commodity-level virtual reality (VR) hardware has made this technology accessible for meaningful applications, such as medical education. Accordingly, in the current work we present a commodity-level, immersive simulation for interacting with human ear anatomy. In the simulation, users may interact simultaneously with high resolution computed tomography (CT) scans and their corresponding, 3D anatomical structures. The simulation includes: (1) a commodity level, immersive virtual environment presented by the Oculus CV1, (2) segmented 3D models of head and ear structures generated from a CT dataset, (3) the ability to freely manipulate 2D and 3D data synchronously, and (4) a user-interface which allows for free exploration and manipulation of data using the Oculus touch controllers. The system was demonstrated to 10 otolaryngologists for evaluation. Physicians were asked to supply feedback via both questionnaire and discussion in order to determine the efficacy of the current system as well as the most pertinent applications for future research.

**Keywords:** Medical visualization, virtual reality, otolaryngology, neurotology, temporal bone, CT scans, 3D reconstruction

## 1. INTRODUCTION

Meaningful applications and techniques are being developed to discern how immersive technology benefits visualization. The medical field provides an especially promising context for this development, as medical practitioners require a thorough understanding of specific 3D structures: human anatomy. In the current work, we evaluate an exploratory system for interacting with 3D anatomical data to better understand how immersive technology can improve our understanding of this multidimensional data. Furthermore, we ask domain experts to interpret the system's utility and potential for future research. The system may be used to improve medical visualizations and to promote future practitioners' understanding of human anatomy.

The aim of medical education, especially anatomy, is to develop a comprehensive understanding of the human body in order to prepare future doctors for interacting with patients. Middle and inner ear anatomy present an especially difficult challenge for medical and surgical education. The structures of interest are complex and small; the largest portion of the cochlea—a spiral-shaped inner ear organ that converts mechanical sound waves into electrical potentials—has a cross-sectional area of only 8.5 x 7 mm.[1] Additionally, the entirety of the middle and inner ear is encased in bone, which presents significant difficulties for visualization and anatomical study using traditional methods.

The most commonly disseminated visualization tools for learning these complex, 3D relationships rely on 2-dimensional (2D) representations. However, when 2D visualizations are used to represent 3D structures, there is a risk of information loss and important interactions between anatomical structures can be absent. Immersive virtual environments may provide a more efficient method for promoting a student's understanding of 3D anatomy. Some prior work that leverages different levels of immersive technology exists for the domain of anatomy education. Semi-immersive and fully immersive displays have been used to develop learning and visualization modules for the anatomy of the heart,[2] the breast,[3] and the abdomen.[4] Research on educational simulations for ear anatomy also exists. However, these studies have primarily been conducted through non-immersive simulation via web-based tutorial[5] and semi-immersive simulation via stereoscopic glasses and computer screen.[6] Although there is evidence that viewing 3D models of anatomy benefits learning,[5,6] it is unclear if stereoscopic viewing provides additional benefits to learning outcomes beyond increased engagement and motivation.[7–9]

While there are few medical simulations dedicated to anatomical education, numerous systems have been developed for surgical training. Some learning effects have been found in haptics-based temporal bone dissections.[6] And the construct validity of other surgical simulations has been verified by exposing performance differences between experienced and novice surgeons.[10,11] These results encourage the use of VR for formative and summative assessment of students. And, as discussed in Arora et al.'s review of virtual training simulations in otolaryngology, VR is suited for proficiency-based curriculum due to its ability to generate repeated practice and informative feedback.[12] However, general evidence supporting the transferability of surgical skills has been variable.[13,14] To better isolate factors that affect this variability–both in system design and evaluation–further research is imperative. In addition, we are interested in the design of commodity-level systems to encourage accessibility. We believe that affordable, sensible solutions could foster more widespread adoption of medical simulation technologies. At present most surgical simulations use expensive haptic feedback devices or commercial software, both of which which present barriers for adoption.

The purposes of the presented work are twofold. The first aim is to discuss a nascent system for ear visualization which leverages commodity-level hardware. The second goal of the paper is to gain preliminary insight from otolaryngologists after using the system to better understand what aspects of our system benefit understanding 3D data and their spatial relationships. The current work is the first in a new line of research which seeks to inform how virtual reality may improve our understanding of 3D data, namely human anatomy, to augment surgical education.

## 2. METHODS

The proceeding section discusses the development and evaluation of the system. Section 2.1 briefly describes the preprocessing which generated the employed data set. Sections 2.2 and 2.3 present the system hardware and immersive virtual environment, respectively. Section 2.4 then provides a detailed description of the interface, before the system evaluation methods are presented finally in Section 2.5.

### 2.1 Data and Processing

The virtual model was created using a cone-beam CT image of a human head acquired with a Xoran (Ann Arbor, MI) xCAT®. The image contains 640 x 640 x 355 voxels that are 0.4 mm isotropic in size. We used automatic techniques to segment the anatomical structures-of-interest in this volume, including active-shape model-based[15] techniques for the scala tympani, scala vestibuli, modiolus,[16,17] and cochlea;[18] graph-based path finding[19] techniques for the facial nerve and chorda tympani;[20] and non-rigid registration-based techniques[21] for the ossicles, external auditory canal, and tympanic membrane.[22] These structures are visualized in Figure 1 and Figure 2.

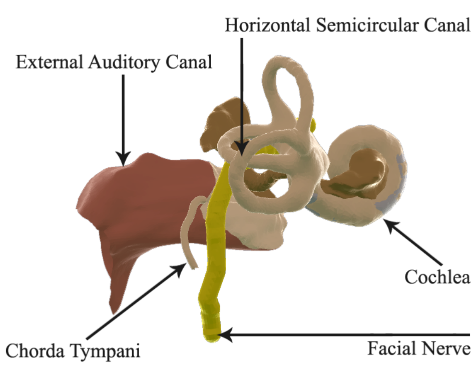


Figure 1. The segmented ear models viewed from the side

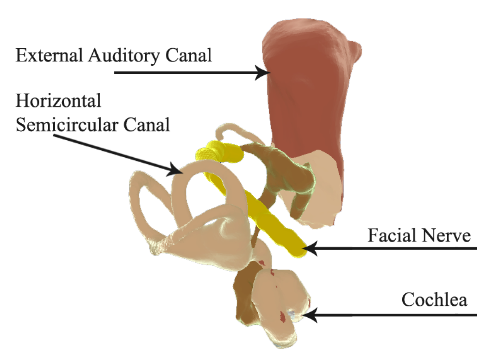


Figure 2. The segmented ear models viewed from above

Additionally, surface models of the skull were created directly from the CT volume. To permit simulating how the view of the surgical field changes as a mastoidectomy—a common otological procedure performed to access the middle ear and other critical structures of the ear—is performed, we created six variant skull models that represent the shape of bony structures at sequential time points in the mastoid resection procedure. To do this, an experienced otologist used custom software developed in-house for editing 3D images to erase tissue in the CT scan in an identical manner to that which would be done when resecting tissue in surgery. This resulted in volumes for six time-points, including no resection, complete resection, and four intermediate time-points. Surfaces models for each time point were created using the marching cubes algorithm.[23] STL files of all of the surface models were converted into FBX files for compatibility in Unity, the game engine in which the simulation was developed.

## 2.2 Materials and Apparatus

The immersive virtual environment was rendered in Unity (version 2017.3.0f3), a multi-platform game engine, and viewed through the Oculus Rift CV1 with 1200 x 1080 per eye pixel resolution. The head-mounted display provided approximately an 110° field of view diagonally and maintained a frame rate of 90 Hz per second. Position and orientation tracking were supported for both the head-mounted display and the two Oculus touch controllers by the native Oculus tracking system, which has a maximum recommended tracking space of 5 x 5 ft. The large tracking space allowed for flexible and realistic walking, promoting users to move themselves as well as the 3D model to better view the anatomy.

## 2.3 Virtual Environment

A 6 x 6 m virtual room (Figure 3) was created for the simulation. At the start of the program, the segmented skull model was placed in the middle of a physical tracking space, which corresponded to the center of the virtual room. For ease of viewing, large 2D planes displaying the images from selected CT scans were positioned in the four corners of the virtual space. The screens displayed one CT scan at a time.

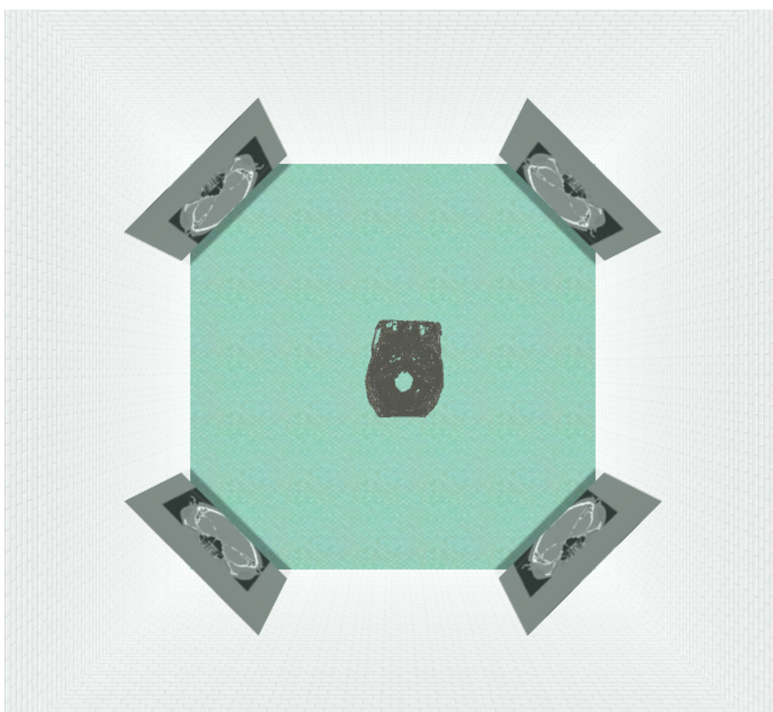

Figure 3. The virtual environment viewed from above

## 2.4 User Interface

The simulation contains several different visualization modes. Users may toggle between two shaders for the skull's appearance: opaque (Figure 4) and transparent (Figure 5). Only the skull model is affected by the transparency, which allows users to view the interior, segmented ear anatomy from a distance with reduced

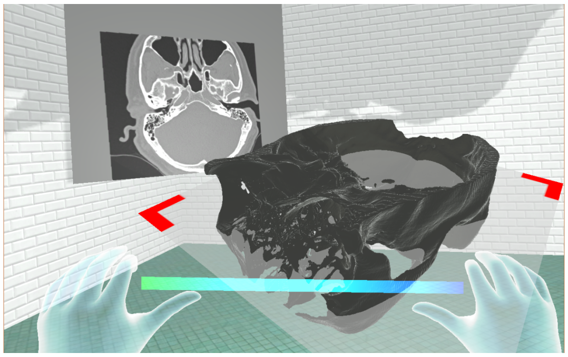

Figure 4. A user scales the skull dimensions in solid viewing mode

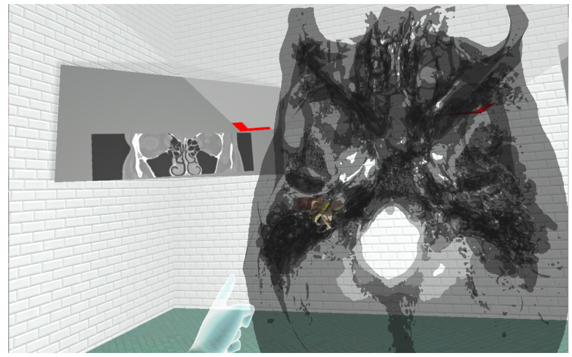

Figure 5. A user observes the position of the ear structures in transparent viewing mode

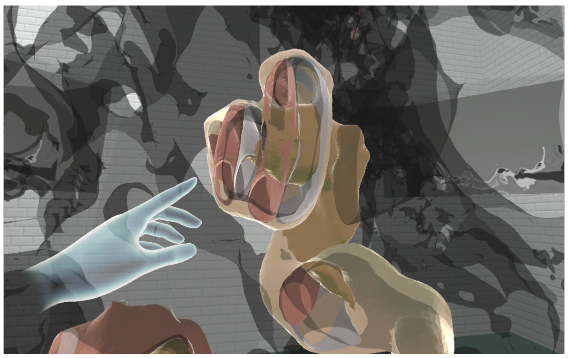

Figure 6. Close viewing of the scala tympani and scala vestibuli within the cochlea

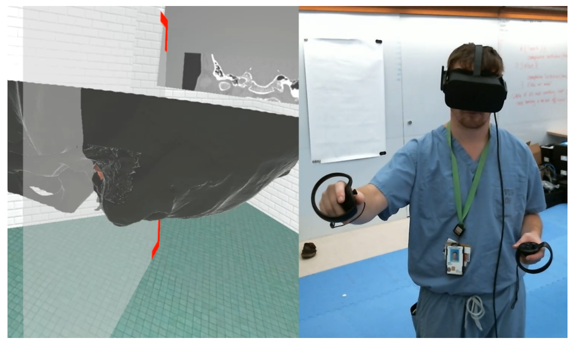

Figure 7. A user navigates the system

occlusion. In addition, users may iterate through six variant skull models, which represent different time points in a simulated mastoidectomy. In effect this sequentially removes bony structures and exposes the middle and inner ear for closer viewing and interaction in both the opaque and transparent visualization modalities. A close view of the exposed inner ear anatomy can be seen in Figure 6.

Using the Oculus touch controllers, users may grab the skull to translate and rotate. Users may also scale the skull model by holding two trigger buttons down simultaneously. This input method utilizes a metaphor similar to the touch interface used in smartphone devices for zooming operations. To enlarge the skull, users pull their hands apart. To shrink the skull, users push their hands together. The scaling factor of the skull is determined by the relative distance between the controllers upon the initial button press–when both trigger buttons are pushed down–and the current position of the controllers. Scaling can be expressed by the equation

$$s_j = s_i + \left(\frac{\Delta\vec{v}_j - \Delta\vec{v}_i}{\Delta\vec{v}_i}\right)\epsilon \tag{1}$$

where $\Delta\vec{v}_i$ is the initial distance between the controllers and $\Delta\vec{v}_j$ is the current distance between the controllers. This value is then multiplied by an epsilon, $\epsilon$, and added to the current scaling factor, $s_i$. A translucent line appears between the user's hands when scaling occurs (Figure 4).

The skull model is intersected by a translucent cutting plane, which can be seen in Figures 4, 5, and 7. This cutting plane maps to a single 2D slice, which is displayed on the screens in the virtual room. To view CT scans aligned with different orthogonal axes of the CT volume, users press a button on their controller. To view different CT slices along a given axis, users grab the cutting plane and move it along the skull. The displayed CT slice on the screens corresponds to the cutting plane's current point of intersection along the skull model. Users may also enhance the size of the screens for closer evaluation of the CT images.

| User Demographic | |
|---|---|
| **Question** | **Response** |
| Q1. Are you a(n): | Student, Fellow, Academic clin, Private practice clin, Other |
| Q2. Are you a(n): | Generalist, Otologist, Other |
| Q3. What is your gender? | Male, Female, Other |
| Q4. What is your age? | — |
| Q5. Have you experienced virtual reality before? | Yes, No |

| System Usability | |
|---|---|
| **Question** | **Response** **Not Very – Very** |
| Q6. Were you successful in using the system? | 1 2 3 4 5 |
| Q7. How easy was it to control the system when exploring the ear anatomy? | 1 2 3 4 5 |
| Q8. Did the system provide a visualization that you found useful? | 1 2 3 4 5 |

| User Understanding | |
|---|---|
| **Question** | **Response** **Not Very – Very** |
| Q9. How familiar were you with the anatomy featured in the demo? | 1 2 3 4 5 |
| Q10. Did the demo better your understanding of the anatomy? | Yes, No, Already an expert |

| Open-Ended Evaluation | |
|---|---|
| **Question** | **Response** |
| Q11. Would you find this useful in clinical practice? | — |
| Q12. What interaction most contributed to your understanding of the anatomy? | — |
| Q13. Do you have any additional comments? | — |

Table 1. System Evaluation Questionnaire

### 2.5 User Evaluation

The system was demonstrated using the same dataset to ten otolaryngologists for preliminary evaluation. After exploring the simulation for a period of approximately 4-7 minutes, the domain experts were asked to evaluate the system with a short questionnaire. The complete questionnaire is presented in Table 1. Participants were also encouraged to think aloud during and after their experience to promote more thoughtful analysis. Written notes were taken to record verbal feedback, and the experimenters directed conversation to obtain more detailed information about pertinent applications for the system as well as how the system benefited participant understanding of human anatomy.

## 3. RESULTS

Overall responses from the questionnaire indicate that the system was easy to control and that it was perceived as useful for clinical practice. Figure 8 shows the results of the system usability evaluation via measures of success, ease-of-control, and usefulness. As the data shows, evaluations of all three measures were positive. Although preliminary, our results are promising and encourage further development of the system.

When otolaryngologists were asked open-ended questions about which interaction they believed contributed most to their understanding of anatomy, five out of ten responses indicated that the ability to move and manipulate the skull was most beneficial. Four comments indicated that the ability to zoom in or be inside the

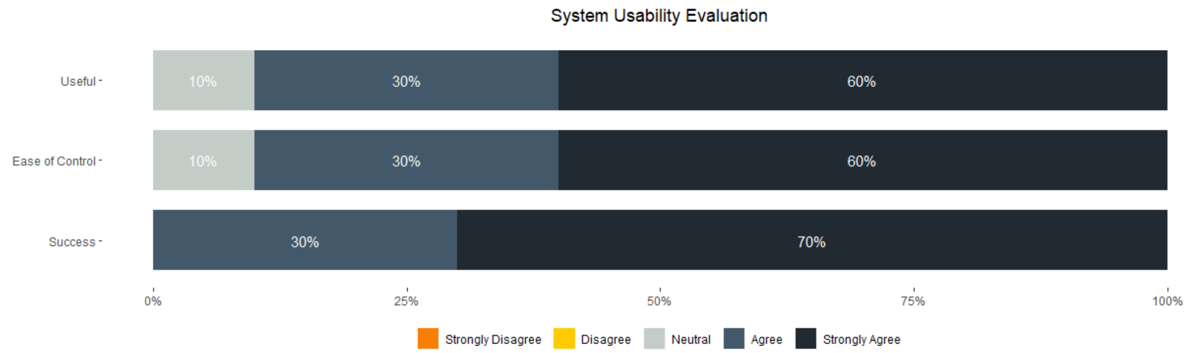


Figure 8. System usability Likert response results

ear—especially the inner ear—was beneficial. The remaining comments suggest that viewing the anatomical relationships in three dimensions and from different angles contributed to the users' understanding of the anatomy. These results suggest that the most beneficial components for improving anatomical understanding in the current simulation were: (1) data manipulation, (2) up-close viewing of small structures, and (3) the ability to view data from multiple angles.

When asked if the simulation would be useful in clinical practice, all participants answered "yes". Several of the physicians were then asked to elaborate on the simulation's utility. They saw immediate applications of the system for training residents and medical students. It was also discussed among the otolaryngologists that the VR system would provide insight and likely improve patient outcomes, if the presented data was available prior to surgical intervention. This benefit can be attributed to the system's use of automatic segmentation, which generates 3D models of a patient's anatomy in a reasonable time without human labor. Most current simulations use manual or semi-automatic segmentation, which is prohibitively time consuming for practical use in the operating room.

## 4. CONCLUSIONS

This study demonstrates a nascent, commodity-level system in which users may interact with anatomical data of the ear in virtual reality. The system was evaluated by domain experts, who expressed that the system was readily usable and that it would be useful in clinical practice. This feedback encourages future development as we seek to ascertain what components of our simulation benefit visualization and as we seek to develop meaningful applications. For the realm of medicine, possible applications are clear. The simulation at present has garnered approval from otolaryngologists as a potential candidate for applications ranging from anatomy education to preoperative planning. Finally, our system is designed to be financially accessible, removing a barrier for adoption experienced by other surgical simulations which rely on expensive proprietary hardware and and solutions.

Although our system has received positive preliminary feedback, there are clear limitations in our assessment. For example, we use a non-validated questionnaire to measure system usability. More rigorous evaluation methods are required to better understand how our simulation and, indeed, immersive technology in general affect the visualization of 3D data. Our current work does little to disentangle the ambiguous effects of stereoscopic viewing on 3D visualizations of anatomy.[7–9] Further validation may be conducted using a combination of standardized, subjective measures (e.g the System Usability Scale) and objective measures (e.g. construct validation). Accordingly, we intend to introduce the next iteration of the system to medical students and residents for validation of the system's efficacy as a visualization tool for anatomy.

In future work we hope to further explore the simulation's utility for education, preoperative planning, and surgical intervention. Context specific tasks allow us to develop behavioral studies in which we may methodically isolate factors that impact virtual reality's benefits and detriments to 3D visualization and learning. Good visualizations promote a better understanding of data. With more detailed evaluation, we can also identify which features of the system best contribute to the development of surgical skills. We are interested in understanding how well spatial knowledge gained from interacting with 3D models in VR transfers when users reason about actual anatomical structures on an ear specimen. Quantifying these results and comparing them against traditional learning methods may allow us to better validate this system as well as its future iterations.

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