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Pre-operative preparation for otologic surgery: temporal bone simulation

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Abstract

Purpose of review—The field of temporal bone simulation (TBS) has largely focused on the development and validation of simulators as training and assessment tools. However, as technology has progressed over the years, researchers have envisioned new clinical applications for simulators extending to pre-operative surgical planning and case rehearsal. The purpose of this article is to review the current state of the art in TBS and to highlight recent advancements in the field. Due to space limitations, we will limit our discussion to computer-based virtual reality (VR) simulators.

Recent findings—A review of the recent literature on TBS revealed very limited application of VR simulators for pre-operative preparation. Current evidence suggests limitations in fidelity preclude successful patient-specific case rehearsal using VR simulation. Further investigation and clinical evaluation are required to validate its use outside of training and skill assessment.

Summary—This article provides an overview of the current use of VR simulators with emphasis on pre-operative planning. We evaluate the limitations of the technology, and discuss potential areas of improvement for the future. More studies are necessary to assess the value of VR simulation for pre-operative preparation.

Keywords

virtual reality simulator; temporal bone; pre-operative simulation

INTRODUCTION

In recent years, the medical field has placed a renewed emphasis on patient safety, thereby promoting the use of simulation in surgery [1]. Temporal bone simulation (TBS) offers users the opportunity to refine their surgical technique prior to performing the procedure on a live

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Conflicts of interest

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patient. While several TBS platforms exist including those making use of physical models, we will limit our discussion to computer-based virtual reality (VR) simulators.

Currently, the vast majority of literature surrounding the use of VR-based TBS provides validity evidence for its use in training of otolaryngology residents. There is very limited data on the use of simulation systems providing a practicing otologist the opportunity to rehearse case-specific procedures. It is postulated that in this application, the surgeon can pre-identify critical areas and pathological variants for eventual consideration during the operation, and practice the surgery on a case-specific model [2]. Until recently, the use of simulation for pre-operative assessment, planning, and rehearsal remained largely speculative. The most recent manuscript published in the last year determined that patient-specific VR simulation for case rehearsal is feasible, but further evaluation is necessary to determine the extent of its clinical value [3]. Although literature on simulation-based pre-operative planning remains relatively sparse, the majority of evidence supports TBS use in training and assessment. We will briefly review the various systems available and what evidence exists in the literature for each regarding pre-operative planning/rehearsal.

CURRENT SIMULATOR PLATFORMS

In a recent review of VR simulator platforms for temporal bone surgery, four were considered validated for training purposes [4]. Only two systems have literature that supports their use in pre-operative planning. Although very little has been reported on the value of these simulators for surgical planning, new advancements in technology will likely promote exploration of their utility outside of training and skill assessment. Each platform is described below.

The Ohio State University Platform

The temporal bone simulator developed at The Ohio State University Wexner Medical Center in conjunction with the Ohio Supercomputer Center utilizes a hybrid rendering system. The OSU simulator demonstrates a strong emphasis on realism and interactivity using direct volume rendering for both haptic (sense of touch) and visual display. Like other simulators, this system utilizes a multimodal platform with visual, haptic, and aural components that combine to provide contextual realism. Features such as the interactive “intelligent tutor” and user options for various types and sizes of burrs, zoom adjustments, and microscope panning were designed to enhance the simulation experience. Since its development in the early 2000’s, several studies, including a large, multi-institutional randomized controlled trial, have demonstrated its utility as a training tool [5–7]. The OSU simulator also offers the ability to integrate new CT imaging data sets for immediate use in the simulator, such as for a patient-specific surgical rehearsal experience [2,8]. Therefore, the OSU system, like its counterparts, exhibits potential for use in pre-operative preparation, but the scope of this application remains to be seen and there have been no studies making use of this platform for case-specific pre-operative planning.

Mediseus®/University of Melbourne Platform

The VR simulator developed at the University of Melbourne, previously marketed as the Mediseus® Surgical Drilling Simulator shares similar features to the other systems mentioned. This system offers a virtual 3D environment with force feedback and manually segmented CT rendering. The user has the option to choose from multiple instruments including a high-speed drill, suction-irrigator, or probe/facial nerve monitor. Distinct from the others, it makes use of a microscope-like interface with a stand-alone, mobile platform. In addition, features such as the transparency or drawing mode, error-reporting systems, and networked haptic feedback enhance the learning experience for the user. As early as 2008, the simulator was shown to exhibit content and predictive validity [9]. Since then, Zhao et al. have reported construct validity and further substantiated its role as a training tool through a randomized control trial [10,11]. Recently, the simulator was validated for competency assessment of cochlear implant surgery [12]. In the last year, the University of Melbourne developed effective automated feedback for the simulator, illustrating a continued emphasis on training [13]. Despite its numerous validation reports, its use in case-specific rehearsal has not been demonstrated in the literature. It is unclear whether this system is still commercially available.

Stanford University Platform

The VR simulator developed at Stanford University, one of the first systems reported in the literature, utilizes CT data with a combination of volume and surface-based 3D rendering. It also contains a haptic interface providing force feedback and vibration. This system has been shown to exhibit construct validity for training and provides features such as haptic mentoring, automated evaluation, and instant feedback producing a potentially ideal environment for independent learning [8,14,15]. Although the TBS system at Stanford has some validity evidence for training, its use in pre-surgical planning has remained limited. Chan et al. reported on the modification and use of this system for pre-operative planning in patients with cholesteatoma. They used a combined pre-operative data set containing both high resolution clinical CT and MRI (FIESTA and PROPELLER sequences) to produce their temporal bone model with cholesteatoma pathology. Image processing and segmentation took approximately 2 hours before the case could be reviewed with their system [16]. Despite demonstrating this capability, their report did not describe a particular case or specific clinical application where the system was actually used prior to surgery.

VOXEL-MAN/TempoSurg®

Currently, the VOXEL-MAN TempoSurg® simulator (Spiggle and Theis, Overath, Germany; www.uke.de/voxel-man) is a commercially available system. Similar to those listed above, this VR simulator utilizes volume rendering to create 3D temporal bone models derived from high resolution CT data. The user controls a drill with a haptic device providing force feedback, and images are displayed stereoscopically. In addition, the user can select from various options such as the view angle and magnification or the type, size, and rotation speed of the drill [17]. Several studies have demonstrated face, content, and construct validity of the VOXEL-MAN simulator as a training tool [4,18,19].

In the last year, Arora et al. concluded that uploading patient-specific CT data onto this simulator to perform surgical case rehearsal is feasible and may have potential in ossicular chain surgery, cochlear implantation, and congenital abnormalities [3]. In this report, participants included a group of trainees and experienced otologic surgery trainers who subjectively rated this system for training and pre-surgical rehearsal. In this instance, the study subjects noted increased confidence after using the system, rating the simulator as highly applicable for planning and training. The trainees overall rated the system higher than the trainers. Specifically with respect to pre-surgical planning, the authors concluded that the VOXEL-MAN simulator shows potential for use in pre-operative preparation, but more studies are needed to confirm its clinical application. They did not report a specific case where the system was used prior to surgery.

In their preliminary analysis on case-specific surgical rehearsal, Arora et al. effectively outlined several limitations of the VR platform. For one, the simulator produced suboptimal representation of anatomical structures with especially poor soft tissue depiction. In addition, the upload process yielded multiple issues including artifact and incomplete CT reconstruction. Finally, poor depth perception upon drilling deeper structures and a lack of auditory cues detracted from the fidelity of the virtual environment. As in most VR simulation studies, the authors promoted the simulator as a beneficial training model for novice surgeons, reporting less confidence in its utility as a pre-operative tool for experienced otologists.

THE ISSUE OF FIDELITY

A more introspective review of Arora's report reveals that the issue of fidelity is the major factor in the implementation of the VOXEL-Man simulator for pre-surgical planning. As mentioned above, experienced otology educators felt that the representation of the dura, facial nerve, and lateral semicircular canal was insufficient. Fidelity of the simulation is dependent upon visual, haptic, and aural representation of the data. Clinical CT data inherently contains only limited information regarding these aspects. In our experience, significant image processing and data enhancement (e.g. coloration) is necessary to provide this information within the simulation. The only image processing (identification and differentiation of clinically significant anatomical structures) performed in the Arora study was "thresholding." Thresholding is a very simplistic method of segmentation where the visualized voxel units are selected based on intensity values (for their report, the threshold value was set at 450 HU). Using the thresholding process is quick and this method alone probably accounts for their acceptable "upload time" of 21 minutes.

These investigators did not report any more advanced image processing procedures to identify and enhance critical landmark structures such as those noted as deficient. The importance of identifying and enhancing these and other critical structures lies in the fact that subtle features of coloration and tactile and aural feedback are necessary to identify and preserve these structures in real surgery. If these cues are not provided in the simulation then identification becomes difficult or almost impossible until the structure is violated; identified by entry into an empty canal or space containing the critical soft tissue landmark. Certainly, repetition can condition the user to identify these structures without violation on subsequent

virtual dissections; however, this process provides improved performance only in the simulation and not in real surgery. It is our opinion that the fidelity of the simulation must be sufficient to allow translation of the learned information directly to the patient in order for it to provide enough impact to be of use. The insufficient fidelity of both the VOXEL-MAN and other current systems appears to be one of the major factors contributing to the lack of widespread use both in training and pre-surgical planning.

The solution to this particular issue is obviously to improve fidelity. This can be done through improved imaging resolution (as pointed out by Arora). Additionally, and perhaps more importantly, improved image processing techniques to identify and enhance critical structures within the image data to match the subtle features encountered during real surgery is necessary for the intended goal. These additional processes can be time-consuming and therefore impact the usefulness of the simulation for both training and pre-surgical planning in a timely or just-in-time fashion. Implementation of automated segmentation algorithms such as that reported by Noble et al. could be useful in cutting down the time needed to identify critical structures [20–22]. Additionally, region enhancement such as coloration, transparency, and soft tissue deformation are critical to developing systems that have direct transference to the real patient. Algorithms that can provide this type of realism from CT generated data do not exist but are currently being developed [23].

Although studies focused on pre-operative TBS have increased in volume over the past year, none have objectively validated VR simulation for nontraditional approaches. At this time, the technology of the simulator platform has not reached a level sufficient for consistent and accurate pre-surgical use. It is our opinion that the limited resolution of clinical CT scans, need for automated segmentation and coloration of structures, lengthy turnaround time all contribute to the current inadequacy of simulators to support pre-operative application in the field.

OTHER SIMULATION-BASED PRE-SURGICAL PLANNING APPLICATIONS

RobOtol

Kazmitcheff et al. used a FEM model of the middle ear with the visual constraints of a 6mm speculum to test different middle ear robotic designs and to train surgeons for clinical use of their middle ear robotic system. This system was not patient specific and was primarily used for robot design [24].

Bonebridge

Matsumoto et al. used a Mimic software simulator with clinical CT scan image data to identify the optimal placement of the Bonebridge active bone conduction implant device prior to actual surgery. A physical template is created from the simulation to guide temporal bone drilling. The physical template is produced by 3D printing methods and the operating surgeon rehearses the procedure using the template developed from the computer-based simulation to assure the accuracy of the template. The template is then subsequently used to guide drilling of the site for implant placement [25].

Histological Rendering

Finally, Kahrs and Labadie provided yet another simulation approach through open access to 3D renderings of human temporal bone histological datasets [26]. These free, publicly available models may be beneficial to surgeons who seek pre-surgical preparation, but lack access to VR simulation or other higher fidelity simulation modalities and are clearly not case-specific.

3D Printing

Although the majority of this review emphasizes VR-based TBS, other studies have proposed using 3D printed temporal bones for pre-operative simulation of challenging otologic cases [27,28]. The anatomical representation of these models has been reported to closely resemble human temporal bones, but minimal data has been published supporting this approach. In a recent study, researchers introduced a gesture-controlled 3D printed temporal bone model using the Microsoft Kinect™ system and proposed case-specific iterations applicable for pre- or intra-operative use [29].

CONCLUSION

Although there is no replacement for actual surgical experience, VR simulation has emerged as a promising option for implementation into training curricula. There is limited experience with using available TBS systems for pre-surgical rehearsal/planning. As technology evolves in the coming years, pre-operative case-specific VR simulation may become more feasible. The utilization of clinical micro-CT scanners will greatly enhance the resolution of patient data. In addition, automated data acquisition, image processing, and algorithms that provide visual and haptic enhancement will optimize the efficiency and accuracy of temporal bone rendering. Finally, advances in the gaming industry will lead to upgraded simulator hardware, thus providing experienced surgeons real-time performance in higher fidelity environments to practice temporal bone procedures. The development of these advanced systems will require long-term financial investment over the course of years. In the meantime, several interesting studies have emerged that suggest a promising future for pre-operative TBS.

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- of special interest
- of outstanding interest

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Key Points

- Currently temporal bone simulators are still relatively nascent and primarily utilized for training and assessment of skill.
- Review of the current literature reveals a feasibility study showing that temporal bone simulators can currently import data from clinical CT scan in a timely fashion but issues of fidelity limit their practical use in active patient surgical rehearsal.
- Additionally, other types of computer-based simulation models have been used to pre-plan surgical approaches such as minimally invasive cochlear implantation and potentially to guide robotic temporal bone surgery but these are still mostly experimental.