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Virtual temporal bone simulators and their use in surgical training: a narrative review

Lauren Bolton[1], Kenneth Young[2], Jaydip Ray[3] and Gaurav Chawdhary[3]

[1]ENT Offices, York Hospital, York and Scarborough Teaching Hospitals NHS Foundation Trust, York UK, [2]ENT, Castle Hill Hospital, Hull University Teaching Hospital, Hull, UK and [3]ENT, Royal Hallamshire Hospital, Sheffield Teaching Hospitals NHS Foundation Trust, Sheffield, UK

Review Article

Lauren Bolton takes responsibility for the integrity of the content of the paper

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Corresponding author:
Lauren Bolton;
Email: lauren.bolton@doctors.org.uk

Abstract

Objective. Temporal bone dissection is a difficult skill to acquire, and the challenge has recently been further compounded by a reduction in conventional surgical training opportunities during the coronavirus disease 2019 pandemic. Consequently, there has been renewed interest in ear simulation as an adjunct to surgical training for trainees. We review the state-of-the-art virtual temporal bone simulators for surgical training.
Materials and methods. A narrative review of the current literature was performed following a Medline search using a pre-determined search strategy.
Results and analysis. Sixty-one studies were included. There are five validated temporal bone simulators: Voxel-Man, CardinalSim, Ohio State University Simulator, Melbourne University's Virtual Reality Surgical Simulation and Visible Ear Simulator. The merits of each have been reviewed, alongside their role in surgical training.
Conclusion. Temporal bone simulators have been demonstrated to be useful adjuncts to conventional surgical training methods and are likely to play an increasing role in the future.

Introduction

Learning to perform various operations on the temporal bone is technically difficult, requiring a high level of appreciation and understanding of three-dimensional (3D) anatomy of the temporal bone. Currently, most otolaryngology trainees augment their in-operation experience with cadaveric temporal bone dissections on sporadic courses to learn to operate safely.[1] However, these methods have implications in terms of availability, accessibility, logistics, costs and patient safety; highlighting the need for other, less-expensive ubiquitous training models that can maintain safety while trainees learn. To this end, groups have employed printed or composite temporal bone models such as the Pettigrew temporal bone.[2]

The coronavirus disease 2019 (Covid-19) pandemic has resulted in widespread significant reduction in otology theatre capacity with a consequent reduction in training opportunities.[3] Despite this, there is a continuing need for trainees to develop operative competence in temporal bone surgery.[4] Virtual reality temporal bone simulators represent a potentially important training platform that could be expanded to bridge the training gap. Here, we outline a narrative review of the literature on virtual reality temporal bone simulators.

Materials and methods

A Medline search was performed between 12 March 2022 and 30 July 2023 using keywords temporal bone, virtual simulation, mastoid surgery, ear surgery and otology (see appendices 1 and 2 of the supplementary material, available online, for the full search strategy). Two authors (LB and KY) independently screened the titles and abstracts for eligibility. Any differences of opinion as to eligibility were discussed until consensus was reached. English language articles on temporal bone simulators and their use in surgical training were included. Articles were excluded if they were not related to virtual simulator use in training for temporal bone dissection. Data were extracted from the papers evaluating simulator validity and use-in-training.

Results and analysis

The Medline search generated 444 results. After screening and removal of duplicates, 61 papers were included in the review. Most available simulators on the market utilise high-resolution computed tomography (CT) scans to generate 3D models of temporal bones that are visualised by 3D glasses. Learners interact with these models using haptic feedback devices.

The Voxel-Man™ Simulator (Voxel-Man Group, Hamburg, Germany; Figure 1) is the most widely validated platform in the literature and was the first commercially available temporal bone simulator. It has a viewing station, haptic feedback device, foot control

Figure 1. Voxel-Man™ Temporal Bone Simulator, image by Christian Stelling.

pedal and central processing system onto which several preprogrammed training scenarios are loaded. Bespoke CT scans also can be input to allow case-specific surgical rehearsal.[5] Melbourne University's Virtual Reality Surgical Simulator was first described using a 'haptic workbench' platform, which can be shared by the instructor and student, however it also can be used with 3D glasses (Figure 2).[6] CardinalSim™ (Stanford University) is a free-access software offering models based on CT scans and using 3D glasses.[7,8] SurgiSim, which was developed from CardinalSim (Calgary, Western and Stanford Universities), utilises the commercially available Oculus™ headset and is compatible with various commercially available haptic feedback devices. SurgiSim includes a virtual operating-room microscope, instrument tray, mayo stand, ceiling-mounted surgical lights and a television screen to make the experience more realistic.[9] Ohio State University (OSU) also has a free-access temporal bone simulator software with data from CT scans and uses a binocular display device (Figure 3).[10,11] Finally, Visible Ear Simulator (Rigshospitalet and Alexandra Institute, Denmark) is a free-access software[12,13] that differs from other platforms as it uses cryosections rather than CT scans to generate models.[14]

Validation, both subjective and objective, is a crucial aspect of deployment of simulation in training. Subjective validity can be divided into face validity (i.e. assessing the realism of the simulator) and content validity (i.e. assessing the training effectiveness and educational value). Objective validity describes the simulator's ability to differentiate between different surgeon experience levels.[15] The literature on validity assessments of the available platforms is summarised in Table I of the supplementary material, available online.[8–10,16–29]

Despite the validation work in the literature, it can be difficult to determine the overall effect of virtual reality simulation on training outcomes in the real world. Indeed, a Cochrane review in 2015, which concluded there was limited evidence to support inclusion of virtual reality simulation into surgical training programmes in ENT, recommended further study.[30] A subsequent meta-analysis showed improvement in overall performance following training on the simulator.[31]

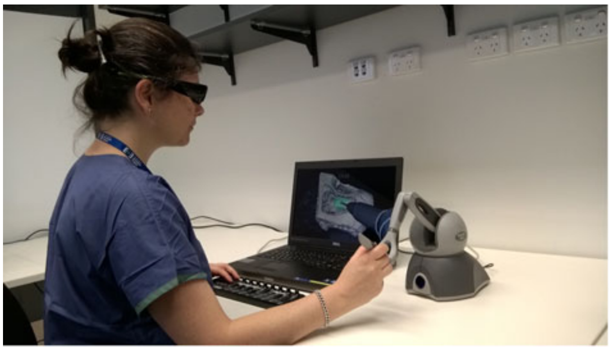

Figure 2. Melbourne University's Virtual Reality Surgical Simulator, image by Dr Sudanthi Wijewickrema.

There is good evidence that the Voxel-Man simulator improves surgical training. Nash *et al.* assessed novice trainees on specific surgical tasks and found improvement in the time taken, overall score and structural damage over the course of the study.[32] Francis *et al.* assessed residents completing two key steps in a cortical mastoidectomy[33] and found improvement in overall score, time taken and number of injuries. Al-Noury assessed four residents performing mastoidectomies on two patients: one case was completed with no simulation training; the second case was performed after practising on the Voxel-Man simulator.[34] Evaluations were conducted by a senior surgeon and nurse. The residents who had used the simulator had a higher global rating score and task-based checklist, as well as a shorter operation time. Furthermore, they felt more confident after utilising the Voxel-Man simulator.[34]

The Voxel-Man simulator has been compared with cadaveric training.[35] Trainees on a two-day mastoid surgery course performed cortical mastoidectomy, atticotomy and posterior tympanotomy on both formats. Trainees judged that cadaveric training was better in terms of resembling real operating conditions and for feedback on their learning. They judged the Voxel-Man simulator to be superior in several domains: providing repetition of a skill, allowing regularity of training, titrating task difficulty, adaptability of teaching method, meeting learning needs and defining clearer goals and outcomes.

Groups have designed curricula around virtual reality simulators. Arora *et al.* developed a Voxel-Man simulator programme for cortical mastoidectomy.[36] This included two familiarisation tasks (skeletonisation of sinodural angle and identification of lateral semicircular canal) and four procedural tasks (short process of incus, delineation of facial nerve and chorda tympani, and extended cortical mastoidectomy). Trainees could not progress to the next step of the curriculum

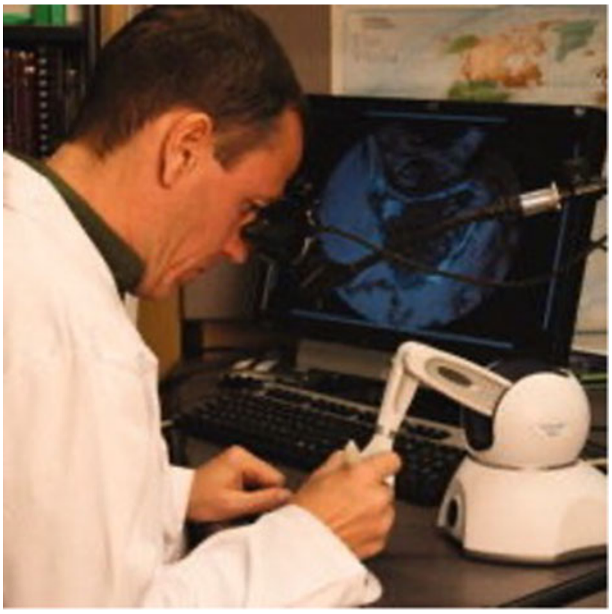

Figure 3. Ohio State University Temporal Bone Simulator.

until meeting minimum requirements of measure, such as bone volume removed correctly, maximum number of injuries, having the burr tip visible and completing the task in a timely manner. A Likert tool showed that trainees found the simulator programme helped them develop hand-eye co-ordination, instrument navigation, drilling technique, surgical anatomy and surgical skills.

The Voxel-Man simulator also has been demonstrated to be useful in avoiding distraction and being able to multi-task.[37] The practical utility of the imported CT scan feature was assessed by Arora *et al.* who found gains in confidence and facilitation of planning and training. Overall, trainees found this function more useful than trainers.[38]

Zhao *et al.* evaluated the usefulness of the Melbourne Temporal Bone Simulator in teaching novice trainees and found that the virtual reality group performed significantly better on cadaveric bones after a self-directed two-hour simulator session as compared to trainees who received traditional teaching.[39] These findings were seen in another study that employed supervised virtual reality teaching.[40] The addition of automated guidance to this simulator was found to further improve performance.[41]

In terms of improving real-world performance, 10 physicians were given five sessions on the Melbourne simulator.[42] They assisted in real cochlear implant surgery following each session. After completing this programme, the participants were scored using a validated tool[43] during supervised surgery and a significant positive association was found between the results of their fifth virtual reality session and their supervised surgery, demonstrating that the simulator improves real world operative performance.[42]

Copson *et al.* assessed otolaryngology registrars performing simulated cochlear implant surgery before and after training on the Melbourne simulator with automated feedback. Performances were assessed using a validated tool and demonstrated significant improvement in total performance scores.[44]

CardiSim was evaluated by Locketz *et al.*[45] Sixteen residents' performances and confidence levels in dissecting a cadaveric temporal bone were evaluated before and after simulated practice. Confidence levels were significantly higher following practice and correlated with increased performance scores.[45]

The Ohio State University Temporal Bone Simulator was evaluated and compared to cadaveric simulation.[10] There was no significant difference in terms of outcomes when evaluated after two weeks of practice, meaning that, at the least, the temporal bone simulator is not inferior to cadaveric practice.

The Visible Ear Simulator has been evaluated extensively regarding its impact on training. Andersen *et al.* found that final performance of residents was comparable between simulator and cadaveric training. They suggested that there is not a significant training benefit of using cadavers over simulation at a junior level, thereby allowing cadaveric materials to be reserved for more-advanced training.[46] Another potential advantage of simulators is the self-directed learning opportunity, potentially as preparatory work before attending a dissection course. Andersen *et al.* demonstrated that self-directed training is effective, especially when distributed rather than massed together.[47] Indeed, automated summative feedback has been shown to improve performance and retention.[48] When utilising virtual reality prior to cadaveric dissection, residents displayed an improvement in performance.[49] This could be related to the lower cognitive load identified in virtual reality training compared to cadaveric training.[50] In addition, regular virtual reality usage prior to a cadaveric course further improved outcomes with cadaveric dissection.[51] Another advantage of simulation is the possibility for decentralised training at home without the need for dedicated dissection labs, which has been shown to improve cadaveric dissection performance.[52,53] Creating a structured self-assessment in a self-regulated training curriculum has been shown to promote cognitive engagement and motivation to learn the task.[54]

However, some studies do present conflicting results. When the Visible Ear Simulator was used by novices, there was no benefit in varying the anatomy.[55] This may simply imply that novices' learning needs are at a more basic level and that nuances in anatomy do not enhance their learning at this level. In another study, ultrahigh fidelity graphics when used by novices seemed to heighten the cognitive load and worsen outcome measures.[56]

The benefit of simulation training also may be procedure dependent. For example, when evaluating the Visible Ear Simulator for cochlear implant procedures, there did not appear to be a benefit when applied to cadaveric training.[57] The effect of repetition in training with the Visible Ear Simulator was evaluated and showed mixed results, motivation alongside supervision and testing are required in addition to individual simulator use.[58]

West *et al.* identified a ceiling effect of the benefit in novices when using the virtual reality simulator and this tended to occur before the 60-minute time limit.[59] This could be improved by improving the tutor function of the simulation.[60] It might also be improved by implementing a structured self-assessment,[61] which has been shown to improve cognitive engagement and motivation[62] as well as cadaveric dissection performance.[63]

A systematic review of mastoidectomy training by Al-Shahrestani *et al.* found insufficient automatic feedback from temporal bone simulators for them to be accepted for certification.[64] Temporal bone simulators are widely used across the world in surgical training.[65–67]

Discussion

All the temporal bone simulators discussed are clearly validated in the literature, thus establishing their place in surgical education. There is a large variation in how these simulators are applied in surgical training and there is not a clearly defined curriculum of how they should be integrated. However, the benefit that these simulators have had on training is well supported by the available literature. This should be utilised to enhance training experience and opportunities, especially in the face of limited training capacity and resources.

Virtual reality simulation is already being utilised in other surgical disciplines to address the Covid-19 training deficit.[68] A LapSim simulator (Surgical Science, Gothenburg, Sweden) was used in general surgery to train how to perform laparoscopic cholecystectomy.[69] There is evidence that it is being utilised as an adjunct alongside other training tools within this specialty.[70]

There are many advantages of training with a virtual reality simulator. Firstly, it is a safe platform to train surgeons without risk of harm to patients. The major advantage of this platform over other training formats is that it allows an almost limitless number of temporal bone dissections and procedures to be performed for free after the initial capital investment. In addition to the repetition, anatomy can be easily adjusted and varied to make appropriate difficulty levels for those at different stages of training. Another advantage is the hyperrealism and coloured critical structures, which are excellent aids to anatomical learning in novices.

All of the simulators have demonstrated that the weakest aspect of the validity assessments was realism of the drill and the haptic feedback; these are areas that could be developed by manufacturers. Aside from this, the literature has established that the models are reasonably well validated, however this is only shown on narrowly defined tasks. Literature showing improvements in real-world global ear surgical performance is limited and future work should address this. Another disadvantage of these simulators is their emphasis on bony dissection, without adequate soft-tissue dissection simulation. As the technology develops, it would be beneficial to incorporate soft-tissue dissection simulation as well as disease dissection and other advanced procedures such as flaps, grafts and cerebrospinal fluid leak repair.

There is a large variability in how the simulators are currently being used. As they become more established and accessible, it will be interesting to review how their regular use and integration into postgraduate programmes can affect surgical training. As high-fidelity simulation becomes more accessible, its usefulness in more-advanced otological procedures would be worth assessing. There are currently mixed reports on their usefulness in cochlear implant simulation training. As the field develops, it would be useful to assess other procedures such as ossiculoplasty or stapedectomy. Potential extended applications include teaching artificial intelligence-assisted robotic arms to perform aspects of temporal bone surgery through supervised and unsupervised learning on virtual reality platforms.

Conclusion

This review demonstrates that temporal bone simulators are an established, validated surgical training tool. They serve as adjuncts to conventional surgical training methods, resulting in improvement in surgical training. Given the reduced availability of surgical-training and operating-theatre time and the need to catch up on this, temporal bone simulators are likely to play an increasing role in future surgical training.

Supplementary material. The supplementary material for this article can be found at https://doi.org/10.1017/S0022215123002025.

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