Virtual reality case-specific rehearsal in temporal bone surgery: A preliminary evaluation

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ABSTRACT

Objectives: 1. To investigate the feasibility of performing case-specific surgical rehearsal using a virtual reality temporal bone simulator. 2. To identify potential clinical applications in temporal bone surgery.

Design: Prospective assessment study.

Setting: St Mary’s Hospital, Imperial College NHS Trust, London UK.

Participants: Sixteen participants consisting of a trainer and trainee group.

Method: Twenty-four cadaver temporal bones were CT-scanned and uploaded onto the Voxelman simulator. Sixteen participants performed a 90-min temporal bone dissection on the generic simulation model followed by 3 dissection tasks on the case simulation and cadaver models. Case rehearsal was assessed for feasibility. Clinical applications and usefulness were evaluated using a 5-point Likert-type scale.

Results: The upload process required a semi-automated system. Average time for upload was 20 min. Suboptimal reconstruction occurred in 21% of cases arising when the mastoid process and ossicular chain were not captured (n = 2) or when artefact was generated (n = 3). Case rehearsal scored highly (Likert score >4) for confidence (75%), facilitating planning (75%) and training (94%). Potential clinical applications for case rehearsal include ossicular chain surgery, cochlear implantation and congenital anomalies. Case rehearsal of cholesteatoma surgery is not possible on the current platform due to suboptimal soft tissue representation.

Conclusion: The process of uploading CT data onto a virtual reality temporal bone simulator to perform surgical rehearsal is feasible using a semi-automated system. Further clinical evaluation is warranted to assess the benefit of performing patient-specific surgical rehearsal in selected procedures.

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1. Introduction

The desire to improve patient safety and training has led to the application of virtual reality (VR) simulation in ENT surgery.1–4 Temporal bone simulation produces a three-dimensional (3D) recreation of the surgical environment. It enables objective assessment of competency in a patient-free, risk-free environment.5 It also offers the possibility of performing case-specific surgical rehearsal (CSSR). The intended surgical procedure may first be performed in an interactive virtual environment using patient-specific computerised tomography (CT) data uploaded onto the simulator.

Procedural skills rehearsal is well established in non-medical fields such as aviation. Bone and Lintern compared conventional map study to simulator rehearsal in 36 pilots preparing for a flight mission.6 A subsequent test of navigation knowledge demonstrated that simulator rehearsal was superior for route knowledge acquisition. The role of VR simulated case rehearsal in carotid endovascular surgery has also been reported.7–10 Results suggest that it facilitates case selection and improves surgical performance.

Several temporal bone simulators have been developed.5,11–13 The Voxelman Temposurg has previously been validated for postgraduate training at Imperial College London and demonstrated adequate face, content and construct validity.2,3,14 However, the process of uploading CT data to a temporal bone simulator to...
perform case rehearsal has not been reported. The objective of this study was to determine the feasibility of performing case rehearsal and identify potential clinical applications in temporal bone surgery.

2. Method

2.1. Ethical considerations

National Research Ethics Service (NRES) reviewed the study and ethical approval was not required under NHS research governance arrangements. The study was exempt from review by Imperial College and Imperial College Healthcare Joint Research Office.

2.2. Participants

Sixteen participants were recruited comprising of 8 otolaryngology trainers (minimum of 400 mastoid operations as primary surgeon) and 8 otolaryngology trainees (mean experience of 19 months). All the trainees had prior experience in temporal bone drilling consisting of laboratory (cadaver (3/8), plastic (7/8)), virtual (8/8) and operating room experience (8/8). Thirty-eight percent (3/8) of the trainee group had previously drilled 2 or more cadaver temporal bones.

2.3. Simulator platform

The Voxelman TempoSurg surgical site is displayed in stereoscopic mode. The operator uses shutter glasses to visualise a 3D representation of the temporal bone. The station houses a computer with software linked to a force-feedback hand device. This serves as a ‘virtual drill’ which is activated by the foot pedal. The drill responds to contact which allows the user to experience changes in pressure. The computer records a number of performance measures such as excessive force. The user is able to alter the surgical orientation, drill size, type, and rotation speed. The 1st iteration of the Voxelman simulator platform was used for this study in which suction and blood functions are not a feature.

2.4. Evaluation of case-specific surgical rehearsal

2.4.1. Feasibility

Twenty-four formalin-fixed cadaver temporal bones were scanned using a Philips iCT 256 CT-scanner. Data were saved in Digital Imaging and Communications in Medicine (DICOM) format to a compact disc for upload using the data import module. The process of reconstruction is described as the ‘segmentation phase’. The user selects a threshold range and converts the data into a 3D voxel model. To enable the model’s orientation to be changed in real time, the image was temporarily converted into a low-resolution surface model (Fig. 1). Data transfer and retrieval were evaluated for: slice spacing and thickness, field of view and intensity range. The segmentation process was assessed for artefact and the threshold required for adequate reconstructions. The time for each temporal bone upload was recorded to assess the learning curve.

2.4.2. Clinical application

Participants were assigned a cadaver temporal bone and its corresponding VR upload. All subjects undertook a standardised 30-min familiarisation session and 90-min temporal bone dissection on the generic simulator training model before performing 3 standardised tasks on the virtual and cadaver temporal bones: extended cortical mastoidectomy, posterior tympanotomy and cochleostomy. Standardised written instructions for each task were provided. Successful task completion was judged by 2 co-authors using a task-based checklist to ensure the objectives were fulfilled (Fig. S1). Following completion, participants assessed the role of case rehearsal and accuracy of representation over 9 domains. Questions were rated on a 5-point Likert scale, in which 1 represented strongly disagree; 2 as disagree; 3 as neutral; 4 as agree; 5 as strongly agree. A score of 4 was the minimum threshold for acceptability. Differences between the trainer and trainee groups were analysed with the independent t-test. A p value of <0.05 was considered significant.

Qualitative data were collected using videos of 90-min focus group sessions where the trainer and trainee groups were independently asked standardised open-ended questions. The videos were saved as digital files, manually transcribed and underwent thematic analysis, as described by Fereday and Muir-Cochrane.

3. Results

3.1. Evaluation of case-specific surgical rehearsal

3.1.1. Feasibility

Each temporal bone had CT data comprising 156 slices, 0.33 mm × 0.33 mm pixel size and 1 mm slice spacing. In all cases, CT-DICOM data were within the standard intensity range. The entire mastoid process was inadvertently not captured in 2
temporal bone scans (an oversight by the radiographer who performed the scan process). There was artefact in 3 temporal bone uploads (Fig. 2) was due to image interference from the attached cadaver identity tags. No areas of artifactual apparent missing bone occurred.

An optimal 3D reconstruction was achieved by selecting a threshold value of 450 Hounsfield units (HU) to define the ossicular chain. The process of using the focus box ensures that crucial anatomy is transferred to the model along with structures surrounding the region. User activity associated with the segmentation process accounted for the majority of the upload time. The time for each upload decreased with experience (mean time: 21 min, range 10–40 min, $R^2 = 0.90$, $p = 0.001$).

3.1.2. Clinical application

The role of case rehearsal and the proportion of positive responses (Likert score >4) regarding adequate representation of simulated anatomy compared to the cadaver model are shown in Table 1. Its role for training scored highly (94%). There was a significant difference in the mean score between the trainer and trainees for this domain only ($p = 0.04$). The ossicular chain was the only positively rated anatomical structure. Dura was rated suboptimal; the most frequently reported limitation was a lack of discernable change in pitch whilst drilling over thin bone such as the tegmen.

Thematic analysis demonstrates the perceived advantages and limitations (Table 2). Participants thought case rehearsal could “refine surgical approach in response to individual patient anatomy”. They also reported that areas of anatomical variation conveyed to the user in the virtual setting influenced subsequent task performance on the cadaver model. This included variant anatomy evident in some of the temporal bones such as the degree of pneumatisation, low dura and high sigmoid sinus ($n = 4$). The following procedures were highlighted as potential clinical applications: ossicular chain surgery, cochlear implantation and congenital bony anomalies. Thematic analysis revealed this was due to adequate reconstruction of relevant anatomical structures and relative lack of soft tissue involved.

Case rehearsal of procedures involving the facial nerve and removal of cholesteatoma were not perceived to be feasible on the existing platform due to “lack of soft tissue reconstruction and suboptimal depth perception during deeper temporal bone dissections”. Three trainers felt that the existing simulator platform needed significant improvement to address the limitations highlighted.

4. Discussion

VR simulation allows unlimited CSSR prior to performing the intended surgical procedure. The results of this preliminary evaluation demonstrate that the upload process is feasible, highlights the limitations of the existing platform and suggests potential clinical applications in temporal bone surgery.

4.1. Feasibility

The upload process is a critical step for acceptance in clinical practice. We were able to identify and overcome difficulties such as inadequate capture. The study demonstrates a streamlined process to enable this to become a useful tool for the practicing otologist.

The technique of reconstruction involved uploading DICOM CT data onto the simulator followed by the segmentation phase. During the CT scanning phase the slice space was 1 mm. Slice spacing is determined by the capability of the CT-scanner and in this study 1 mm was the narrowest distance possible. A publication by the Voxelman group suggests that optimal results are obtained using isotropic voxels with a slice spacing of 0.4 mm. In this study, pixel size was 0.33 mm × 0.33 mm with 1 mm slice spacing. The degree to which accuracy of representation in the simulator was affected by using 1 mm slice spacing is not known although non-isotropic image data could potentially affect this. An interesting study would be to use finer slice spacing and repeat the evaluation. Re-scanning the cadaver temporal bones following dissection for comparison with their drilled simulation uploads would be another way to assess the accuracy of VR uploads.

With regards to the upload process, a linear regression model demonstrated a significant reduction in the upload time. The primary reason for this was an improved understanding of the segmentation process. More cadaver temporal bones ($n = 24$) than participants ($n = 16$) were used to allow margin for error. There is an inevitable selection bias as the first 8 uploaded temporal bones were not used. Artefact occurred in 3 and in a further 2 the mastoid process was not included in the scan.

The aim during segmentation is to create an accurate 3D representation of the intended image. The segmentation process is
Surgical planning and rehearsal

Pre-operative planning

Pre-operative rehearsal

Affects approach and equipment required intraoperatively

Trouble shooter of potential issues

Cannot rehearse certain procedures

Suboptimal face validity for some structures

3D anatomy

3D visualisation of anatomy

Aid conceptual jump from 2D images to operative 3D anatomy

Less useful for the experienced surgeon

Suboptimal 3D depth perception on deep dissection

Improve surgical performance

Improve skills and confidence specific to procedure

Particularly relevant for junior trainees

VR realism may limit skills progression in senior trainees

e.g. lack of auditory cues during the procedure: egg-shelling over sigmoid sinus

Safety

Informed risk analysis and case selection

Fewer complications

Additional tool when evaluating procedural success

Combination of clear evaluation of risks with visualisation of anatomy

Human factors

Case success not purely dependent upon anatomy

Unaccounted for by case rehearsal

Table 2
Summary of advantages and limitations of case-specific surgical rehearsal.

<table>
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<tr>
<th>Advantages</th>
<th>Reason</th>
<th>Limitations</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surgical planning and rehearsal</td>
<td>Pre-operative planning</td>
<td>Affects approach and equipment required intraoperatively</td>
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</tr>
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<td></td>
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</tr>
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<td>3D anatomy</td>
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<td>Aid conceptual jump from 2D images to operative 3D anatomy</td>
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<td>Improve surgical performance</td>
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<td>Informed risk analysis and case selection</td>
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<td>Combination of clear evaluation of risks with visualisation of anatomy</td>
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<td></td>
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<td>Unaccounted for by case rehearsal</td>
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There was consensus regarding lack of a role for case rehearsal in cholesteatoma surgery due to suboptimal soft tissue reconstruction and poor depth perception when drilling deeper structures (Table 2). The latter is a limitation of this simulator in both user-uploaded and preloaded temporal bones. This suggests that high levels of realism are necessary for this clinical application.

It is important to differentiate between the simulation environment alone and the use of case-specific data. All subjects performed a standardised temporal bone dissection on the generic training model and their response to this acts as a control. Anatomical accuracy and use as a training tool were rated to a higher level with pre-loaded cases. However, surgical planning was rated higher with case-specific data as compared to the training model (Table 3) indicating that case rehearsal confers a novel advantage distinct from the generic simulator program.

5. Comparisons with other studies

Parameters governing operative outcome are challenging to establish; in particular, safety gains are difficult to quantify. In vascular surgery, case rehearsal has been shown to improve patient safety by enabling acquisition of new skills without risk to the patient. Studies of procedural rehearsal in carotid endovascular surgery suggest that case-specific simulation rehearsal can influence the instrument selection and surgical approach in the operating room. Furthermore, the same authors have reported that case rehearsal is more effective than a generic simulator-based warm-up or no warm-up. Patient specific simulation rehearsal is relevant in temporal bone surgery because in otological practice the use of a preoperative CT scan is considered by many to be helpful.

6. Study limitations

Limitations include the small cohort and data interpretations must bear this in mind. The 5-point Likert scale is subjective, limiting participants' responses to specific questions. Using another scale or cut-off point could produce a different picture of usefulness. Self-surveys provide a low level of evidence and subjective evaluation is a limitation of all validation studies.

Table 3
Comparison of generic simulation and case specific environments. All domains scored out of a maximum of 5. Significant differences between the groups are highlighted.

<table>
<thead>
<tr>
<th></th>
<th>Simulator</th>
<th>Case specific data</th>
<th>p Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accuracy of anatomical structures</td>
<td>4.1</td>
<td>3.5</td>
<td>0.04</td>
</tr>
<tr>
<td>Training tool</td>
<td>4.4</td>
<td>4.3</td>
<td>0.33</td>
</tr>
<tr>
<td>Surgical planning</td>
<td>3.7</td>
<td>4.1</td>
<td>0.02</td>
</tr>
</tbody>
</table>
Metrics of task performance are a feature of the generic training model although this does not occur with user-uploaded models. In this study, evaluation of task completion was independently performed using a task-based checklist involving a binary result (achieved or not). This limits the scope for assessment of progression.

Trainers are not necessarily experts in surgical education. Nevertheless, their opinion provides a useful barometer of the efficacy of simulation for preoperative planning. An experienced surgeon who is able to conceptualise a 3D image may not benefit from this technology. It is unsurprising that the trainees rated the system more highly than trainers in this regard. The trainees had sufficient otolaryngology experience which provides a reasonable basis for comparison with other training methods. This group may find simulated case rehearsal more useful than trainers due to greater familiarity with computer-based technology and better appreciation of their own learning needs.

6.1. Limitations with the simulator platform

One of the major limitations of the simulator is the absence of soft tissue definition. Qualitative analysis revealed this was a recurring theme. The shortcoming related to lack of soft tissue could be addressed by CT/Magnetic Resonance Imaging (MRI) fusion. A reproducible method for combining CT and MRI temporal bone images has been reported in a different simulation platform to rehearse cholesteatoma surgery. The authors suggest that this method is accurate enough to represent tumour tissue, fluid distribution and important bony landmarks such as the facial nerve canal.21

7. Conclusion

This preliminary assessment of feasibility provides a comprehensive approach to CT upload for performing case-specific rehearsal in temporal bone surgery. Limitations with the existing simulator platform confine the clinical applications to procedures not requiring soft tissue reconstruction. Further technological developments are needed to expand the clinical applications. Nevertheless, simulation-based case rehearsal represents a useful adjunct to the existing methods of pre-operative patient evaluation. Clinical evaluation is necessary to determine whether this will actually improve the surgeon’s performance in the operating room and ultimately improve patient safety.

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Author contribution

Mr Asit Arora — Conception and design of study, acquisition of data; drafting the article and revising it critically for important intellectual content; final approval of the version to be published.
Ms Chloe Swords — Data acquisition and interpretation; drafting the article and revising it critically for important intellectual content; final approval of the version to be published.
Mr Sam Khemani — Data acquisition, analysis, revising it critically for important intellectual content; final approval of the version to be published.
Mr Zaid Awad — Data acquisition, analysis, revising it critically for important intellectual content; final approval of the version to be published.
Professor Ara Darzi — Conception and design, revising article critically and final approval of the version to be published.

Mr Arvind Singh — Data acquisition, analysis, revising it critically for important intellectual content; final approval of the version to be published.

Mr Neil Tolley — Conception of study, revising the article critically for important intellectual content; final approval of the version to be published.

Conflict of interest

The authors have no conflicts of interest to declare.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.ijsu.2013.11.019.

References