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Integration of High-resolution Data for Temporal Bone Surgical Simulations

Gregory J. Wiet, MD, FACS, FAAP^{2,3,4}, Don Stredney, MA^{1,3}, Kimerly Powell, PhD², Brad Hittle¹, and Thomas Kerwin, PhD¹

Gregory J. Wiet: Gregory.wiet@nationwidechildrens.org; Don Stredney: Don@osc.edu; Kimerly Powell: Kimerly.powell@OSUMC.edu; Brad Hittle: bhittle@osc.edu; Thomas Kerwin: Kerwin@osc.edu

¹Ohio Supercomputer Center, Biomedical Research Group, 1224 Kinnear Road, Columbus, Ohio 43212 USA

²The Ohio State University, Department of Biomedical Informatics, 250 Lincoln Tower, 1800 Cannon Drive Columbus, Ohio 43210 USA

³The Ohio State University, Department of Otolaryngology, 4000 Eye and Ear Institute, 915 Olentangy River Road, Columbus, Ohio 43212 USA

⁴Nationwide Children's Hospital, Department of Otolaryngology, 700 Children's Drive, Columbus, Ohio 43205 USA

Abstract

Purpose—To report on the state of the art in obtaining high-resolution 3D data of the microanatomy of the temporal bone and to process that data for integration into a surgical simulator. Specifically, we report on our experience in this area and discuss the issues involved to further the field.

Data Sources—Current temporal bone image acquisition and image processing established in the literature as well as in house methodological development.

Review Methods—We reviewed the current English literature for the techniques used in computer-based temporal bone simulation systems to obtain and process anatomical data for use within the simulation. Search terms included “temporal bone simulation, surgical simulation, temporal bone.” Articles were chosen and reviewed that directly addressed data acquisition and processing/segmentation and enhancement with emphasis given to computer based systems. We present the results from this review in relationship to our approach.

Conclusions—High-resolution CT imaging (100µm voxel resolution), along with unique image processing and rendering algorithms, and structure specific enhancement are needed for high-level training and assessment using temporal bone surgical simulators. Higher resolution clinical scanning and automated processes that run in efficient time frames are needed before these

Corresponding Author: Gregory J. Wiet, MD, FACS, FAAP, Department of Otolaryngology, Nationwide Children's Hospital, 700 Children's Drive, Columbus, Ohio 43205, Gregory.wiet@nationwidechildrens.org, Phone: 614.722.6804, Fax: 614.722.6609.

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systems can routinely support pre-surgical planning. Additionally, protocols such as that provided in this manuscript need to be disseminated to increase the number and variety of virtual temporal bones available for training and performance assessment.

Keywords

Temporal bone imaging; surgical simulation; High-resolution imaging; microCT; image processing

Introduction

There is an essential need to provide a safe and effective method for the deliberate practice of surgical technique to both learn and maintain performance [1,2]. Knowledge gained through experience must be integrated through deliberate practice with adequate feedback to ensure safe performance. Repeated attempts are required to test aspects that involve not only a consummate comprehension of the intricate regional anatomy, but also to master the subtle psychomotor interactions and variations of specific techniques.

There are many issues in resident education that exasperate the ability to deliberately practice surgical techniques outside of the operating theater. These include: limits to duty hours, procurement, processing, and maintenance of cadaveric specimens, and health risks associated with exposure to human tissue [3,4]. All of these issues present impediments to obtaining adequate time to practice and hone one's skills. Consequently, many surgical residencies turn to the use of simulation-based instruction to augment traditional methods for providing surgical training. For otologic surgery, this has traditionally been provided in the temporal bone cadaveric lab, the above issues notwithstanding. Structurally accurate surgical simulation environments also hold promise to support pre-surgical planning, development of minimally invasive approaches, and robotic surgery.

Integral to the use of simulation, whether physical or virtual, is the quality or fidelity of the representation of the regional anatomy. The purpose of this review is to provide a summary of the state of the art of the techniques and methods used to create the representation in computer based temporal bone simulation. We provide a review of the current methods and issues associated with visual and haptic realism, the challenges associated with striking a balance between realism and functional interaction, and what we perceive as the future direction the field is heading.

The accurate representation of the regional anatomy is one of the "sine qua nons" for the simulation to be useful. A major component of simulation training is the sensory (visual and haptic) fidelity of the simulation. The endeavor to develop and demonstrate simulator efficacy, begins with development of adequate fidelity of the simulation. The simulation environment must be sufficient to support the educational objectives [5]. Additional concepts such as validity build upon demonstration of adequate fidelity. Several groups have as their objective, to provide a computer based simulation platform sufficient in training to obtain proficiency and mastery in otologic surgery and assessment of skill [6–13]. This can only be achieved with adequate fidelity to support advanced procedures. An additional expectation of the data is to drive auditory and tactile representations. Furthermore, the

representation must be of a high enough fidelity to engage both the novice and the more seasoned operator. Essential in the assessment of skill is to provide enough fidelity to differentiate levels of expertise (not just novice from expert). It is our experience that the fidelity of most temporal bone simulators (other than cadaveric bones) available today lags behind what is required to achieve these goals.

A wide variety of methods, physical and virtual, are being employed to emulate the regional anatomy used in training simulations. Each method has its advantages and disadvantages. Physical models can be quite elegant, such as those employing 3-D printing techniques derived from computed tomography. New composite materials are being explored to provide increasing variance into intricate models. Many (including our group), have chosen to explore the use of virtual representations [6–13]. Through the technique of direct volume rendering, we have developed a system to support otologic surgery, specifically that of a complete mastoidectomy with a facial recess approach. As is the case with many computer based temporal bone simulators, our past developments, based on virtual reconstructions from clinical scanners, were limited in spatial resolution and found to be insufficient to fully support techniques beyond the basic [14]. The need to provide enough fidelity for more advanced procedures requires higher resolution of structural data and innovative methods to exploit higher resolution acquisitions.

Whether physical or virtual, the anatomical simulation is dependent upon the resolution and processing of the image data used to produce the model. In most instances, computer-based simulation accomplishes this by 3D reconstruction of the regional anatomy using data from clinical imaging. Others have employed high-resolution photography utilizing data from specialized cadaveric preparations, including data from the National Library of Medicine's Visible Human Project and the Visible Ear Project [10, 11]. Some have employed methods to extract polygonal surfaces from these data, while others have created representations using volumetric techniques. The benefit of maintaining volumetric representation of the bone is that internal detail is preserved, as opposed to only the outer shell of structures, as provided by a polygonal model. The drawback to this approach is the high amount of data required, and the computational power required to render the large dataset in real time.

Noting the current limitations in image quality in most computer based temporal bone simulators, we have acquired data from micro computed tomography (μ CT). We define μ CT as an isotropic voxel (volume element) dimension of at most 100microns. Although clinical scanners can achieve in-plane resolution of 100microns, their through-plane resolution is two to 4 times greater. The resulting data from μ CT present astonishing levels of detail, approaching that seen in human tissue under the operating microscope. A balance is needed to provide high enough resolution to support the detail necessary to provide sufficient fidelity to support advanced procedures, with extreme amounts of data that cannot be rendered in real-time (i.e. 20–30 frames per second in stereo). In our opinion, clinical resolution scans lack detail, albeit, the signal to noise ratio is high and proprietary image processing techniques performed as part of the scanning protocol enhance structures of clinical interest. The μ CT provides high detail but there is a lower signal to noise ratio that challenges the delineation of fine structure from background using automated techniques. The main factor currently preventing use of higher resolutions with clinical CT is the higher

radiation dose required to achieve the same resolution. Cone beam scanners are approaching this resolution and in the future may provide sufficient resolution to rival that of the μ CT with less radiation. This will promote the use of simulation platforms for more in-depth pre-surgical planning or procedural rehearsals on patient specific data. This manuscript presents a review of the current state of the art methodology for image acquisition, image processing, segmentation, and structural enhancement to provide adequate detail to support higher-level simulated otologic surgical procedures and assessment. We compare our techniques to that used in other temporal bone surgical simulation platforms.

Methods

We reviewed the current English literature for the techniques used in computer-based temporal bone simulation systems to obtain and process anatomical data for use within the simulation. Search terms included “temporal bone simulation, surgical simulation, temporal bone.” Articles were chosen and reviewed that directly addressed data acquisition and processing with emphasis given to computer based systems. No living human beings were involved as study subjects therefore Institutional Review Board approval for this study was not necessary. This is consistent with the policy of the DHHS and The Ohio State University Office of Responsible Research [15].

Results

1. Data Acquisition

As noted earlier, most of the current temporal bone simulation platforms make use of clinical resolution CT data [8, 9, 12, 13]. The use of clinical scanners provides a ubiquitous source for acquiring image data. Additional advantages include that data sets can be acquired in vivo, and therefore can provide pathological variation, acquisitions are not center dependent, and there is significant signal processing built into clinical scanners that provides less noisy data. Secondly, image data acquired from a clinical scan could be used expediently for pre operative planning and surgical rehearsal [16, 17]. The disadvantages of such systems primarily revolve around the lack of resolution needed to support high fidelity simulation of advanced procedures. Not surprisingly, μ CT provides greater detail from higher resolution [5, 18]. However, with the higher resolution come challenges in rendering and processing the data to make it suitable for simulation. Issues involved in using μ CT data include the lower signal to noise ratio, the lack of preprocessing and the size of the data.

Using a unique approach, Sorensen et al. [10, 11] gathered structural data directly from images of a sectioned cadaveric head. Digital images were acquired of a cryosectioned head at 25micron thickness creating a ultra high resolution data set composed of 605 RGB images with in plane resolution of 3056 x 2032 pixels aligned with custom registration software. This large data set was cropped to a functional resolution of 50microns per pixel; a resolution comparable to μ CT. However, this approach is considerably more involved, time intensive and not conducive for multiple acquisitions.

We have previously reported on the use of both clinical and μ CT data for simulation [18]. In our initial experience, we proposed an approach to simultaneously use both data sets in a

registered fashion and “swap” between the two depending on the level of magnification called for by the user. This approach was found to be problematic because of memory constraints updating two registered volumes and performance issues when calculating haptic feedback simultaneously in real time. We found that using a μ CT image with an intermediate isotropic resolution of 100 microns was the best solution for visualizing all of the structures of interest and maintaining real-time response with the haptic feedback.

Others have used CT temporal bone data for 3D visualization not necessarily associated with surgical simulation. There are a variety of image processing and rendering applications for handling this type of data. Meshik et al, [19] and Theunisse et al, [16] discussed the use of clinical and μ CT to create 3D models for the purpose of planning the optimum path for cochlear implantation. Both groups used AMIRA, a commercial imaging software application (Visage Imaging, Carlsbad, USA) to manually segment structures from 2D images and create 3D models. Meshik used both clinical and μ CT and fused the two to provide high-resolution verification of the location of the scala tympani chamber in the cochlea. Chan et al, [20] also used this same software package to create a 3D model for their temporal bone dissection simulator. Lee et al, [5] developed a custom software system to visualize middle ear structures using volume rendering similar to our VolEditor software (see below). They point out the limitation of previous proprietary volume rendering software that “run exclusively on proprietary clinical scanners and has not been optimized to run on the commodity hardware currently available on desktop workstations. Similarly, available software cannot easily manage the large size of the high-resolution datasets from micro-CT scanning.” Their system runs on commodity based hardware and provides transfer function capability as well as both physical and haptic display.

Specifically, at our institution, temporal bone specimens are acquired through the Body Donation Program at The Ohio State University. Bilateral excisions are performed using standard harvesting techniques [21]. Micro-CT imaging was performed using a Siemens Inveon™ cone-beam μ CT imaging system. An excised temporal bone was scanned using 80 kVp, 500 mA, 200 ms exposure time with an isotropic voxel size of 98.77 μ (matrix=928x928x896). All micro-imaging is conducted at the Wright Center of Innovation at The Ohio State University.

2. Image Processing and Segmentation

Identification and preservation of specific structures is the hallmark of proper surgical technique. To enhance fidelity and subsequent feedback during surgical simulation, portrayal of the same structural characteristics seen in surgery must be present to identify individual landmarks. Each individual voxel in the volume is given a tag associated with an anatomical structure. There are few or even no inherent features in the data to delineate many areas critical for surgical simulation automatically. By accurately delineating specific structures one not only enhances the fidelity of the simulation by allowing structure specific appearance modification, one also provides the basis for assessment of surgical performance [22, 23]. Tracking tool selection, pressure, velocity and direction of movement, etc. in relation to the landmark structures can be used in determining proper or improper maneuvers near critical areas within a simulation. Tracking the violation of structures during a drilling

procedure is also used as a specific metric. These performance characteristics provide vital information on surgical technique and having the ability to track and record these metrics is a distinct advantage of computer-based training systems.

Most systems today use a process of “thresholding” and manual outlining of specific anatomical structures of significance [6–13]. Thresholding is a simplistic method of segmentation where the visualized voxel units are selected based on intensity values. Manual segmentation of structures where an individual outlines the anatomical boundaries on a single slice and repeats the process until the entire three-dimensional structure is outlined is very time consuming and dependent upon the expertise of the individual performing this function. Sorensen et al found that manual segmentation of their cryosectioned specimen took upwards of 550 man-hours to segment both bony and soft tissue structures [10].

In our system, the μ CT data is preprocessed by segmenting bone from background and soft tissue by applying a global threshold based on inspection of the volume histogram (Fig 1a). This results in a segmented bone image with limited soft tissue. Small debris and ‘floaters’ are removed from the volume using a 2D connected components labeling algorithm (Fig 1b) [24, 25]. Objects less than 100 pixels = 0.77 mm³ in size are discarded. This segmented bone volume is used to mask the grey level image used for rendering (Fig 1c and d).

We have developed software (VolEditor™) that can be used to interactively label structures and regions of importance within extremely large data sets (>2 GB). VolEditor™ exploits the power of the graphics-processing unit (GPU) to interactively render large volumetric data sets. This allows us to import data sets immediately for viewing and manual 3D labeling.

VolEditor provides key interactive manipulation of the data in three dimensions at the full acquisition resolution (100 microns) in *real time*. The program provides a rendering of the data including arbitrary orientation (rotate/pan/zoom) and sectioning. These basic functions allow for optimal positioning and examination of key areas. To assure critical structures have been properly identified, a structure can be followed along its natural pathway by employing various viewing angles e.g., the facial canal can be traced from the internal auditory canal through to the stylomastoid foramen. Views from the middle ear verify proper identification and smaller structures associated with the nerve. For example, the chorda tympani branch can be verified by identifying continuous branching from the main trunk. (Fig 2)

VolEditor automatically crops data sets too large to load into video memory constrained by the GPU hardware. Thereafter, the user can interactively select sub-regions of the data for focused segmentation. These key features allow for intuitive, accurate and expedited segmentation of voxel elements associated the specific structures of surgical significance. Currently, we segment up to 40 different structures per temporal bone.

To delineate or label key structures with subjective boundaries, e.g., temporal line, VolEditor provides the key function of “painting” voxels in 3D. These areas are then “labeled” and identified through name, color, and numerical index. Note: this “painting” is for demarcation of boundaries, and is not to be confused with coloration (Fig 4).

Recent research into automatic segmentation based on manually segmented reference volumes has been promising. Most current atlas-based techniques start with affine registration between a training volume and a volume to be segmented followed by non-rigid registration of the volumes. The two-step approach increases accuracy and decreases computation time. Reda et al. [26] describes a method where the centerline of the structure to be segmented is transferred from the reference volume and then grown using a level set approach. Noble et al. [17] takes a slightly different approach where the boundaries of the entire structure are transferred to the volume to be segmented and then iteratively optimized using a statistical shape model. Even these approaches are of limited use when segmenting structures have very little local differentiation, such as the temporal line. In the future, we hope to adapt some of these automated segmentation features into our processes to reduce the human interaction necessary to identify structures of importance.

3. Structural Enhancement

In high-resolution CT acquisitions of the temporal bone, soft tissue structures are often not resolved in great detail. Further noise reduction applied to enhance the bone may also degrade the soft tissue signal. Additionally, what soft tissue information the CT provides, does not attribute features such as color or physical characteristics necessary for haptic display. For simulation of the mastoidectomy procedure, we are concerned mostly with specific soft tissue structures that are associated with a bony canal. For example, the facial nerve lies within the Fallopian canal. The canal can be clearly seen in CT image data. In most systems, soft tissues are recreated by selecting voxels associated with the space within bony canals that house the tissue. This is a process of segmentation however once these voxels are selected, they need to be individually enhanced to portray properties associated with the structure in question. For instance, voxels that are associated with the facial nerve will need to be differentiated on the basis of color, etc. from the surrounding bone. Likewise, voxels associated with structures such as the dura and sigmoid sinus will also need to be colored to provide enough fidelity so that they can be identified and manipulated as they are in real surgery. The usefulness of the simulation will depend on the ability of the system to provide sufficient fidelity of real life cues to allow adequate transference of technique. Providing coloration and aspects of physical interaction are necessary features.

Sorensen and his co-authors avoid this issue of voxel enhancement for visual fidelity by using their cryosection methodology by which the natural soft tissue coloration is obtained directly from the photographic image of the section for cadaveric specimens [10,11].

Like others, we recreate soft tissue structures using information from the segmented canal that is subsequently enhanced with structure specific attributes. The labeled voxels used to identify landmark structures are further processed for coloration. Each structure uses a lookup table that associates CT Hounsfield units with colors. These lookup tables are developed in concert with clinical experts such that they are visually consistent with what is observed in a real surgery. We use a constrained transparency function on the bone surrounding these structures, giving a slight translucent effect similar to what is seen with thinning bone over a structure during a physical surgery. We modulate the transparency based on the distance from the structure. For example, in coloring specific surfaces and

volumes associated with the sigmoid sulcus, and indirectly the sigmoid sinus, the voxels surrounding the sigmoid sulcus are used to set the translucency of the associated volumes so that color change observed when approaching the sinus is similar to that seen in a real surgery. As one removes bone around the sigmoid sinus, the thinning of the bone provides a level of transparency by which the blue hue of the sinus is visible. For the dura mater, a pink to gray tone is applied. For the facial nerve, white/pink coloration is applied with a red outline. Specific color and transparency features are necessary for a number of structures throughout the temporal bone and need to be rendered correctly for adequate visual fidelity. (Fig 4)

Without the need for segmentation the time to import scanner data to the simulation takes approximately 20 minutes in our system: Pre processing ~ 5 minutes, coloration ~ 15 minutes. Depending on the number of structures to be identified, the time for segmentation is dependent upon the user's experience and facility with the manual segmentation software. We are exploring automated processes to accelerate this as mentioned above. Similar timing has been described using clinical resolution data and thresholding as the segmentation process for the VOXEL-man system [8, 9, 27].

4. Rendering challenges

In general, high quality real-time volume rendering is used in medicine and other fields with the data sizes used in all the referenced simulators. It is important to note a substantial difference between the requirements of most volume rendering tools with that of a surgical simulation involving tissue removal. Most volume rendering tools focus on passive viewing, where the data is fixed and only viewing parameters (such as coloring, clipping planes, or camera position) are altered in real-time. In volumetric surgical simulation, the content of the volume is changed by the user in real-time in a non-deterministic way,. The user is modifying the volume by drilling away the bone. This modification prevents effective use of much of the pre-processing that is done in a passive viewing context that allows higher quality rendering at interactive frame rates.

A task in diagnostic medicine that has similar requirements as mastoidectomy simulation is real-time streaming 3d ultrasound reconstruction. Solteszova et al. [28] present a visibility-based filtering technique to speed up rendering of constantly changing volumetric data. In ultrasound, all of the volume is changing whereas with surgery simulation, only a small workspace is changing at once. They get rendering speeds of around 5–10 fps depending on the volume size; their largest size is 256^3 voxels, the volumes we are using are around four times that size.

Hardware accelerated ray tracing systems such as Nvidia's Optix [29] and Intel's Embree [30] have achieved real-time ray tracing performance for geometric models, and offer scalability for larger models. At this time, those systems have not focused on volumetric data, such as those that come from CT or MRI. Therefore, in their current implementation they are not suitable for volumetric-based surgical simulation, although modifications could be done to make them a more desirable platform in the future.

There have been advances in physically based rendering techniques that would change the filtering and colorization procedure. However, achieving real-time performance for visual rendering while modifying the volume is a very difficult task. Approaches like those in the Exposure renderer are promising [31]

Conclusions and Implications

For a simulation to be effective, it must provide sufficient fidelity to allow successful accomplishment of the educational and/or assessment goals of the exercise. Fidelity is linked to the resolution of the regional anatomy. The level of fidelity will vary depending on the desired pedagogical goal. For instance, if the educational objective is to teach medical students anatomy of the temporal bone for a general understanding, then the three-dimensional reproduction of the major elements such as the ossicular chain, cochlea, labyrinth and their relationships to the regional nerves and vessels may be sufficiently accomplished by reconstruction of clinical image data.

However, if the objective is mastery of surgical technique, or for high-stakes assessment, then a higher level of visual fidelity is necessary. Arora and colleagues in a systematic review of otolaryngology specific simulators note that the current systems may have some applications for training junior level trainees but do not support advanced procedures [32]. As an example, Laeeq et al. found that differences in performance levels were more evident for more complex procedures that require a greater level of detail and fidelity [33]. Malik stated that high fidelity simulators that better simulate more challenging anatomy may advance skill faster than even cadaveric specimens. Additionally, support for more complex procedures is necessary to support advanced milestones for higher-level learning [34]. In particular, these authors state the trans-mastoid approach to the middle ear, known as the facial recess approach, needed to be supported to differentiate the higher-level performers. This approach requires proper representation of both the facial nerve and its branch, the chorda tympani nerve. The chorda tympani nerve varies in diameter between 0.3 – 0.5mm. Noble et al 2008 were able to resolve and segment this structure in clinical resolution scans – 0.3 x 0.3 x 0.4mm voxel size [35] for the purposes of pre-surgical planning for cochlear implant surgery. The Voxel-Man system uses 0.33 x 0.33mm in plane resolution and 0.4 to 1mm slice thickness [8, 27]. In our experience, however, a resolution of 0.1 x 0.1 x 0.1mm voxel size was necessary to provide sufficient detail to reliably identify and process the associated voxels for proper representation in our simulator (Fig 5).

As a separate but related issue, haptic display fidelity has also been shown to be insufficient for higher-level applications of temporal bone surgical simulation. Ioannou in 2014 evaluated the effect of fidelity on performance of expert temporal bone surgeons using the system developed by O’Leary et al at the University of Melbourne. They compared drilling techniques to those used by the same experts on real temporal bones. The authors found that drilling technique was different in the simulation and discussed the aspect of fidelity with respect to the haptic model used for the virtual simulation [36].

We have presented ours and other’s work regarding the acquisition and processing of image data for temporal bone surgical simulation. We discuss techniques that are necessary to

provide adequate detail to support advanced procedures to both train and assess surgeons operating in this complex region. Using these new approaches, we and others are continuing to iteratively improve temporal bone simulation systems. As the simulation fidelity increases, the usefulness of the simulation expands to potentially include high stakes assessments such as graduation from residency training, board certification and maintenance of skill. Only after the technological challenges to provide adequate visual and haptic fidelity have been overcome, can the task of simulation validation begin. These subsequent steps will require significant resources to demonstrate such things as predictive validity, positive skill transfer and impact on patient outcomes. From our perspective, there still exists significant issues related to acquiring and processing image data acquired in vivo that is sufficient enough to support complex pre-operative surgical rehearsal. As clinical scanners approach μ CT resolution with limited radiation exposure, the usefulness of simulations in this application will become more commonplace. Software packages that provide automated processing of image data will also need to be developed so that activities such as segmentation and structure enhancement can be provided without significant human interaction.

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References

1. Ericsson, KA. Acad Emerg Med. Vol. 15. United States: 2008. Deliberate practice and acquisition of expert performance: a general overview; p. 988-94.
2. Edelman DA, Mattos MA, Bouwman DL. FLS skill retention (learning) in first year surgery residents. J Surg Res. 2010; 163:24–28. [PubMed: 20605587]
3. Scott A, De R, Sadek SA, Garrido MC, Courtney-Harris RG. Temporal bone dissection: a possible route for prion transmission? J Laryngol Otol. 2001; 115(5):374–5. [PubMed: 11410127]
4. NIOSH 2011 = NIOSH Skin Notation Profiles: Formaldehyde/Formalin, [CAS No. 50-00-0] DHHS(NIOSH) Publications No.2011-145 April 2011
5. Lee DH, Chan S, Salisbury C, Kim N, Salisbury K, Puria S, Blevins NH. Reconstruction and exploration of virtual middle –ear models derived from micro-CT datasets. Hearing Research. 2010; 263:198–203. [PubMed: 20100558]
6. Wiet GJ, Bryan J, Dodson E, Sessanna D, Stredney D, Schmalbrock P, Welling B. Virtual temporal bone dissection simulation. Stud Health Technol Inform. 2000; 70:378–84. [PubMed: 10977577]
7. Wiet GJ, Stredney D, Sessanna D, Bryan JA, Welling DB, Schmalbrock P. Virtual temporal bone dissection: an interactive surgical simulator. Otolaryngol Head Neck Surg. 2002 Jul; 127(1):79–83. Review. [PubMed: 12161735]
8. Pflesser B, Petersik A, Tiede U, Höhne KH, Leuwer R. Volume cutting for virtual petrous bone surgery. Comput Aided Surg. 2002; 7:74–83. [PubMed: 12112716]
9. [accessed May 5, 2015] <http://www.voxel-man.com/simulator/ent/VOXEL-MAN%20ENT%20Flyer.pdf>
10. Sørensen MS, Dobrzeniecki AB, Larsen P, Frisch T, Spørring J, Darvann TA. The visible ear: a digital image library of the temporal bone. ORL J Otorhinolaryngol Relat Spec. 2002; 64:378–381. [PubMed: 12499759]

11. Sorensen MS, Mosegaard J, Trier P. The visible ear simulator: a public PC application for GPU accelerated haptic 3D simulation of ear surgery based on the visible ear data. *Otol Neurotol.* 2009; 30:484–487. [PubMed: 19546800]
12. Sewell C, Morris D, Blevins NH, Dutta S, Agrawal S, Barbagli F, Salisbury K. Providing metrics and performance feedback in a surgical simulator. *Comput Aided Surg.* 2008; 13(2):63e81. [PubMed: 18317956]
13. O'Leary SJ, Hutchins MA, Stevenson DR, Gunn C, Krumpholz A, Kennedy G, Tykocinski M, Dahm M, Pyman B. Validation of a networked virtual reality simulation of temporal bone surgery. *Laryngoscope.* 2008; 118(6):1040–6. [PubMed: 18354339]
14. Wiet GJ, Stredney D, Kerwin T, Hittle B, Fernandez SA, Abdel-Rasoul M, Welling DB. Virtual temporal bone dissection system: OSU virtual temporal bone system: development and testing. *Laryngoscope.* 2012 Mar; 122(Suppl 1):S1–12. [PubMed: 22294268]
15. <http://orrrp.osu.edu/files/2012/02/Research-Involving-Human-Subjects.pdf>.
16. Theunisse HJ, Gotthardt M, Mylanus EA. Surgical planning and evaluation of implanting a penetrating cochlear nerve implant in human temporal bones using microcomputed tomography. *Otol Neurotol.* 2012 Aug; 33(6):1027–33. [PubMed: 22805103]
17. Nobel JH, Labadie RF, Majdani O, Dawant BM. Automatic Segmentation of Intra-Cochlear Anatomy in Conventional CT. *IEEE Trans Biomed Eng.* 2011 Sep; 58(9):2625–2632. [PubMed: 21708495]
18. Wiet GJ, Schmalbrock P, Powell K, Stredney D. Use of ultra-high-resolution data for temporal bone dissection simulation. *Otolaryngol Head Neck Surg.* 2005 Dec; 133(6):911–5. [PubMed: 16360513]
19. Meshik X1, Holden TA, Chole RA, Hullar TE. Optimal cochlear implant insertion vectors. *Otol Neurotol.* 2010 Jan; 31(1):58–63. [PubMed: 19707168]
20. Chan S, Li P, Lee DH, Salisbury JK, Blevins NH. A virtual surgical environment for rehearsal of tympanomastoidectomy. *Stud Health Technol Inform.* 2011; 163:112–8. [PubMed: 21335772]
21. Nadol JB. Techniques for human temporal bone removal: information for the scientific community. *Otolaryngol Head Neck Surg.* 1996; 115:298–305. [PubMed: 8861882]
22. Wiet G, Hittle B, Kerwin T, Stredney D. Translating surgical metrics into automated assessments. *Stud Health Technol Inform.* 2012; 173:543–8. [PubMed: 22357055]
23. Kerwin T, Stredney D, Wiet G, Shen HW. Virtual mastoidectomy performance evaluation through multi-volume analysis. *Int J Comput Assist Radiol Surg.* 2013 Jan; 8(1):51–61. [PubMed: 22528058]
24. Shekhar R, Zagrodsky V. Mutual information-based rigid and nonrigid registration of ultrasound volumes. *IEEE Tran Med Imaging.* 2002; 21(1):9–22.
25. Gonzales, RC.; Woods, RE. *Digital Image Processing.* Addison-Wesley, Reading; Massachusetts: 1992.
26. Reda FA, Noble JH, Rivas A, McRackan TR, Labadie RF, Dawant BM. Automatic segmentation of the facial nerve and chorda tympani in pediatric CT scans. *Med Phys.* 2011 Oct; 38(10):5590–600. [PubMed: 21992377]
27. Tolsdorff B, Petersik A, Pflesser B, Pommert A, Tiede U, Leuwer R, Höhne KH. Individual models for virtual bone drilling in mastoid surgery. *Comput Aided Surg.* 2009; 14(1–3):21–7. [PubMed: 19557582]
28. Solteszova, Veronika; Birkeland, Asmund; Viola, Ivan; Bruckner, Stefan. Visibility-driven processing of streaming volume data. *Proc of VCBM.* 2014:127–136.
29. Parker, SG.; Bigler, J.; Dietrich, A.; Friedrich, H.; Hoberock, J.; Luebke, D.; McAllister, D.; McGuire, M.; Morley, K.; Robison, A.; Stich, Martin. OptiX: a general purpose ray tracing engine. In: Hoppe, Hugues, editor. *ACM SIGGRAPH 2010 papers (SIGGRAPH '10).* ACM; New York, NY, USA: 2010. p. 13Article 66DOI=<http://dx.doi.org/10.1145/1833349.1778803>
30. Wald I, Woop S, Benthin C, Johnson GS, Ernst Manfred. Embree: a kernel framework for efficient CPU ray tracing. *ACM Trans Graph.* 2014; 33(4):8. Article 143 July 2014. <http://dx.doi.org/10.1145/2601097.26011991>.

31. Kroes, T.; Post, FH.; Botha, CP. Exposure Render: An Interactive Photo-Realistic Volume Rendering Framework. PLOSone. 2012 Jul. (<http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0038586>)
32. Arora A, Swords C, Khemani S, Awad Z, Darzi A, Singh A, Tolley N. Virtual reality case-specific rehearsal in temporal bone surgery: A preliminary evaluation. *Int J Surg*. 2014; 12:141–145. [PubMed: 24316389]
33. Laeeq K, Bhatti NI, Carey JP, Della Santina CC, Limb CJ, Niparko JK, Minor LB, Francis HW. Pilot testing of an assessment tool for competency in mastoidectomy. *Laryngoscope*. 2009 Dec; 119(12):2402–10. [PubMed: 19885831]
34. Malik MU1, Varela DA, Park E, Masood H, Laeeq K, Bhatti NI, Francis HW. Determinants of Resident Competence in Mastoidectomy: Role of Interest and Deliberate Practice. *Laryngoscope*. 2013 Dec; 123(12):3162–7. [PubMed: 23878112]
35. Noble J, Warren F, Labadie R, Dawant B. Automatic segmentation of the facial nerve and chorda tympani in CT images using spatially dependent feature values. *Med Phys*. Dec.2008 35(12)
36. Ioannou I, Avery A, Zhou Y, Szudek J, Kennedy G, O’Leary S. The effect of fidelity: how expert behavior changes in a virtual reality environment. *Laryngoscope*. 2014 Sep; 124(9):2144–50. Epub 2014 Jun 3. DOI: 10.1002/lary.24708 [PubMed: 24715702]

Fig. 1.
a,b,c,d – Pre-processing steps: a.) Globally thresholded clinical data, b.) Removal of extraneous objects using connected components and size threshold, c.) Masked clinical data and d.) MicroCT data using the segmented mask shown in part b.

Fig. 2. screen capture of VolEditor software showing a manually segmented facial nerve (yellow) and other structures. Note multiple windows providing additional data processing features able to be applied to the volume data set in real time.

Fig. 3. demonstration of the VolEditor “painting” capability for demarcation of boundaries such as the temporal line as highlighted in the image.

Fig. 4. virtual microscope view. Note the coloration and transparency of the sigmoid sinus (blue tint) and the facial nerve (pink tint). Bright red areas represent feedback to the user where the specified structure has been violated.

Fig. 5. Comparison of main trunk of the facial nerve (A) and chorda tympani branch (B) in μ CT (left) and clinical resolution CT (right).