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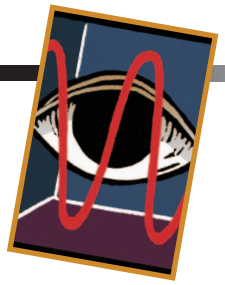

# A Virtual Laboratory for Temporal Bone Microanatomy

*By Pei-Dong Dai, Tian-Yu Zhang, Jim X. Chen, Zheng-Min Wang, and Ke-Qiang Wang*

LOCATED IN THE LATERAL CRANIAL BASE, THE TEMPORAL BONE IS ONE OF THE HUMAN BODY'S MOST COMPLICATED PARTS. IT CONTAINS MANY TINY, DELICATE, AND DETAILED ANATOMICAL STRUCTURES, INCLUDING MANY IRREGULAR ORIFICES, ANTRA (cavities), canals, and fissures. Crucial nerves, blood vessels, and auditory and vestibular organs coexist in this dense bone structure in a complex 3D configuration, causing medical science to once regard the temporal bone as a surgically forbidden area (see Figure 1). Today, otolaryngology (ear, nose, and throat) surgeons still find it difficult to envision and master these complex anatomic interrelationships.

The stapes, for example, is one of the three bones in the middle ear. These bones transmit sound vibrations from the tympanic membrane to the inner ear. In a disease called otosclerosis, the stapes becomes fixed and doesn't transmit sound efficiently. A stapedectomy is a procedure that removes the top part of the stapes, drills a hole in the stapes footplate, and places a prosthesis 0.6 mm through the footplate to transmit sound. This prosthesis, a small column approximately 0.5 mm in diameter, must not touch the utricle or saccule; if it does, there is a high risk of postoperative deafness. An otolaryngologist can perform a stapedectomy successfully only when he or she is familiar with the 3D relationship among these tiny structures.

Learning temporal bone microanatomy is one of an otolaryngology resident's most important and problematic tasks. Traditionally, the process involves anatomic description, illustrations, photographs, histological (minute structures) and gross sections, computerized tomography (CT) and magnetic resonance imaging (MRI) scans, sculpted specimens, and, finally, cadaver dissection and operating room surgical procedure observation. It takes intensive study spanning hundreds of hours and many laboratory trial-and-error efforts before an otolaryngology resident is confident enough to begin drilling in the operating room.

Equipping a traditional temporal bone laboratory equipped with operating tables, operating microscopes, high-speed otologic drills, and otologic microinstruments is very expensive.[1,2] Moreover, human temporal bone specimens taken from individuals who have donated their bodies to the hospital are not easy to get for training or study. Even with such tools, otolaryngology surgeons won't have all the important 3D structural relationships simultaneously and interactively.

Here, we present a new method for generating and reconstructing 3D temporal bone models and their applications in stereoscopic virtual environments. Our virtual laboratory and its associated software can run on ordinary PCs.

## The Recent Past

In recent years, computer-generated 3D temporal bone models have proven their potential to be the ideal teaching or study aid. Several authors have published different CT-scan-based 3D temporal bone models and virtual surgery simulations for training.[3–5] However, CT-scan-based 3D models are coarse and only contain bony structures, because a CT scan's low resolution precludes generating any tiny structures.[6–8]

Other 3D models use a series of human temporal bone histological sections.[9–11] This general method is decalcified celloidin-embedded bone specimen processing. This is a laborious process—taking approximately five months—and involves several procedures, including fixation, decalcification, embedment, and sectioning. When removing the temporal bone from a cadaver, the specimen must be immediately placed within fixative solution (formalin) to preserve tissue morphology. Undecalcified temporal bone can't be sectioned under common microtomy conditions because calcium, a metal, destroys steel knives' cutting edges. After it's decalcified in acid, the specimen is dehydrated in increasing concentrations of ethyl alcohol. After this, the specimen is embedded in celloidin, which penetrates the specimen and hardens by evaporation, making it easily sectioned because it forms blocks that are

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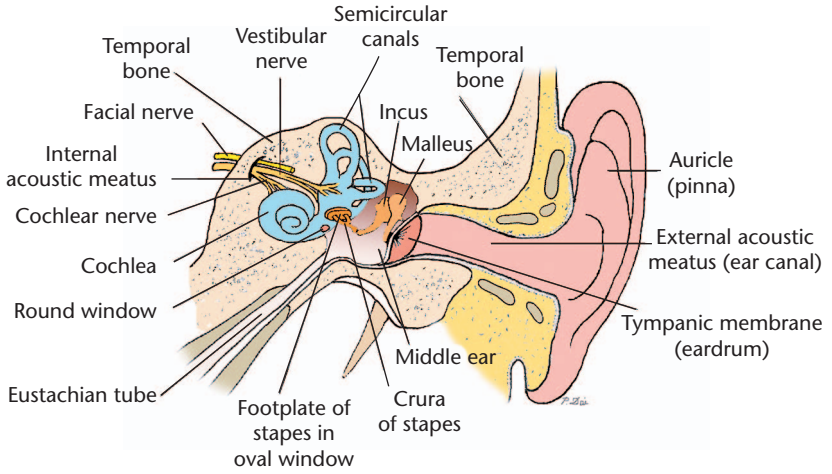


**Figure 1. Schematic showing structures of the middle and inner ear within the temporal bone. The middle ear consists of a Eustachian tube (a canal that links the middle ear with the throat area) and three ossicles (malleus, incus, and stapes) that are connected and transmit sound waves to the inner ear. The inner ear consists of cochlea (containing the nerves for hearing), vestibule (containing receptors for balance), and semicircular canals (containing receptors for balance).**

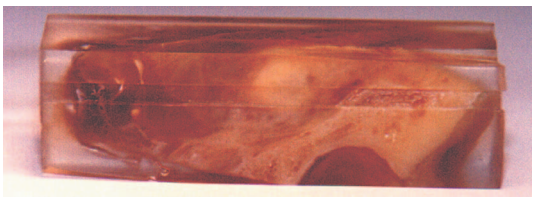

**Figure 2. The undecalcified polymer-embedded temporal bone block. After being fixed in formalin, the temporal bone block was dehydrated and then immersed in a methylmethacrylate (MMA) solution until the MMA polymerized to a solid block. A heavy-duty sliding microtome sectioned the block into serial slices.**

more supportive to large specimens.

Unfortunately, full decalcification and dehydration softens, distorts, and shrinks bone specimens. These disadvantages can create partially inaccurate 3D models.[12] Moreover, previous studies couldn't successfully reconstruct tiny structures such as membranous vestibular organs, branches of the nerves, small irregular canals, and compartments in temporal bone. These limitations significantly hampered existing computer-based temporal bone models from becoming effective virtual platforms.

## Materials and Methods

To reconstruct more accurate and detailed temporal bone 3D data for our study, we applied a process that doesn't distort or shrink specimens. The operations include specimen preparation, image processing and section alignment, and data segmentation and surface reconstruction.

### Specimen Preparation

We obtained a fresh otologic-disease-free temporal bone from a donor and prepared a 40 × 25 × 25-mm specimen block that included the complete middle and inner ear, a portion of the mastoid process (the bony projection behind the ear), and the upper part of the jugular bulb (a temporal bone cavity that connects two large veins) to be fixed in formalin (a preservative). We punched a small hole in the tympanic membrane, and drilled into the arcuate eminence (a prominence on the temporal bone) so that formalin could quickly enter the middle and inner ear antra. After dehydrating the specimen block via immersion in graded aqueous ethanol solutions, we immersed it in xylene (for transparency), and then in pure methylmethacrylate (MMA). It was then immersed in MMA+dibutylphthalate+benzoyl peroxide at room temperature until the MMA polymerized into a solid block.[12] The process took approximately one month. Using a milling machine, we cut, milled, and polished the undecalcified polymer-embedded block into a glabrous (a surface without projections) cuboid. Figure 2 shows the result. We then cut the cuboid horizontally into a series of 50-micron-thick sections using a heavy-duty Leica SM2500S sliding microtome (Leica Microsystems, www.leica-microsystems.com). We stained all the sections with hematoxylin and eosin for better visualization, and mounted them on slides. We obtained a total of 201 film section slides.

### Image Processing and Alignment

Using a high-resolution transparency scanner, we directly scanned the histological slides and saved them as BMP files with 24-bit color depth at a resolution of 1,320 × 1,024 pixels—approximately 0.02 mm per pixel. Using Adobe Photoshop 6.1, we processed all images by increasing their contrast and sharpening their margins until the borders of every structure in each histological section were clear and easy to discern. We aligned these images manually by comparing, translating, and rotating adjacent slides with respect to one another and by superimposing one over the next. The frame of reference for

the alignment was each slide's outline border and the temporal bone's regular structures, such as air cells in the mastoid process, the cochlear canal, semicircular canal, and vessels.

### Data Segmentation and Surface Reconstruction

Using SURFdriver (3D reconstruction software developed jointly at the University of Hawaii and the University of Alberta; www.surfdrivermaps.com), we precisely traced the contours of specific structures and reference points from magnified images displayed on a computer monitor (see Figure 3). Although SURFdriver includes automatic contouring using edge detection based on color threshold values, we obtained satisfactory results only when we manually defined the contour edge points by following visible color lines and tissue morphology separations. The manual process also eliminated possible software-induced contouring errors. We chose anatomic structures of interest for their usefulness in studying temporal bone surgical microanatomy, including organs, inner cavity surfaces, all canal types, vessels, and nerves and their branches.

SURFdriver joined the individual segmented data set to form a tiled surface representation of the 3D geometry (see Figure 4), which could be exported to a standard CAD document exchange format (DXF) or Initial Graphics Exchange Specification (IGES) format. This process used the marching cubes algorithm, which produces a triangular mesh by computing isosurfaces from discrete data. By connecting the patches from all cubes on the isosurface boundary, we get a surface representation. We exported each 3D model in DXF to 3ds max modeling software (Discreet; www.discreet.com) and recombined them to produce the finished model, using a unique color for each object in the temporal bone. Because of some subtle alignment errors, we used 3ds max's MeshSmooth filter on these raw objects to produce smooth surfaces. We were able to construct almost all of the left temporal bone features including many tiny structures that weren't previously available (see Figure 5).

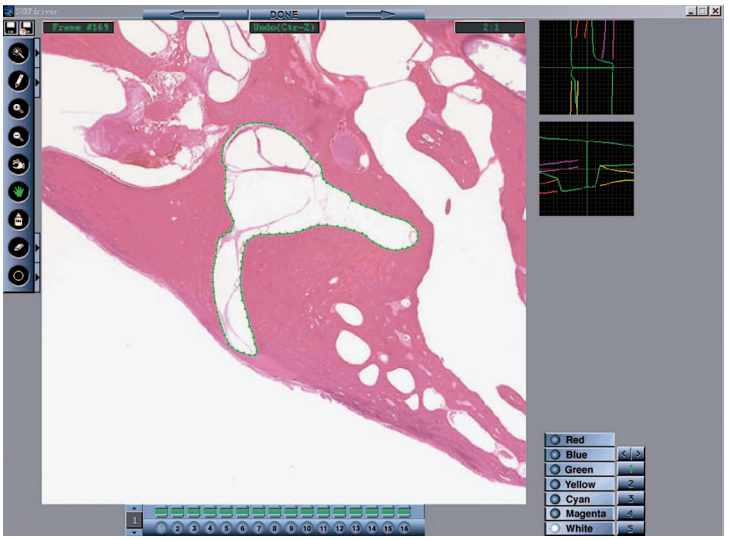


**Figure 3. Tracing the bony labyrinth's contour. Using SURFdriver 3D reconstruction software, we manually traced the contours of interesting structures by following visible color lines and tissue morphology separations.**

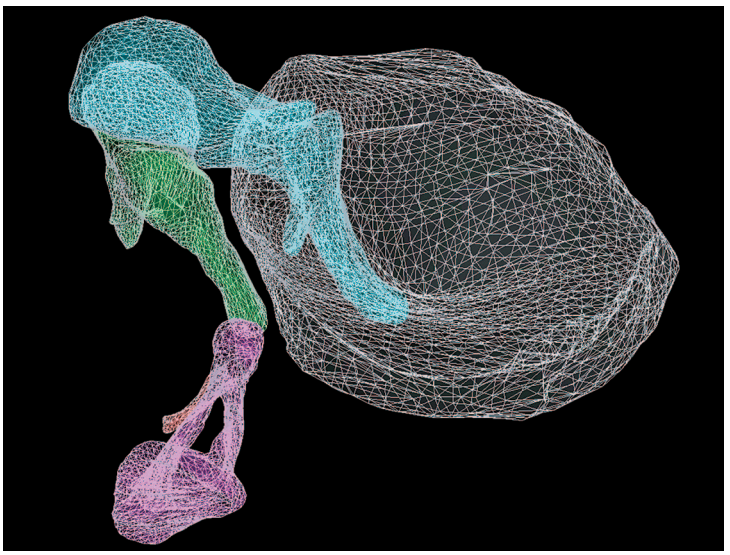

**Figure 4. The tympanic membrane and auditory ossicles. SURFdriver joined the individual segmented data set to form a tiled surface representation of the 3D geometry by using the marching cubes algorithm.**

### The Virtual Laboratory

Beijing Sunstep View-Tech Development Co. (www.pcvr.com.cn/) built the VR X6000A virtual laboratory in the Eye and ENT Hospital at Fudan University in China. This laboratory (see Figure 6) consists of a SunGraph 6000A virtual reality (VR) workstation and SYSEditor 5.0 software, a 3D VR modeling software platform, a two-

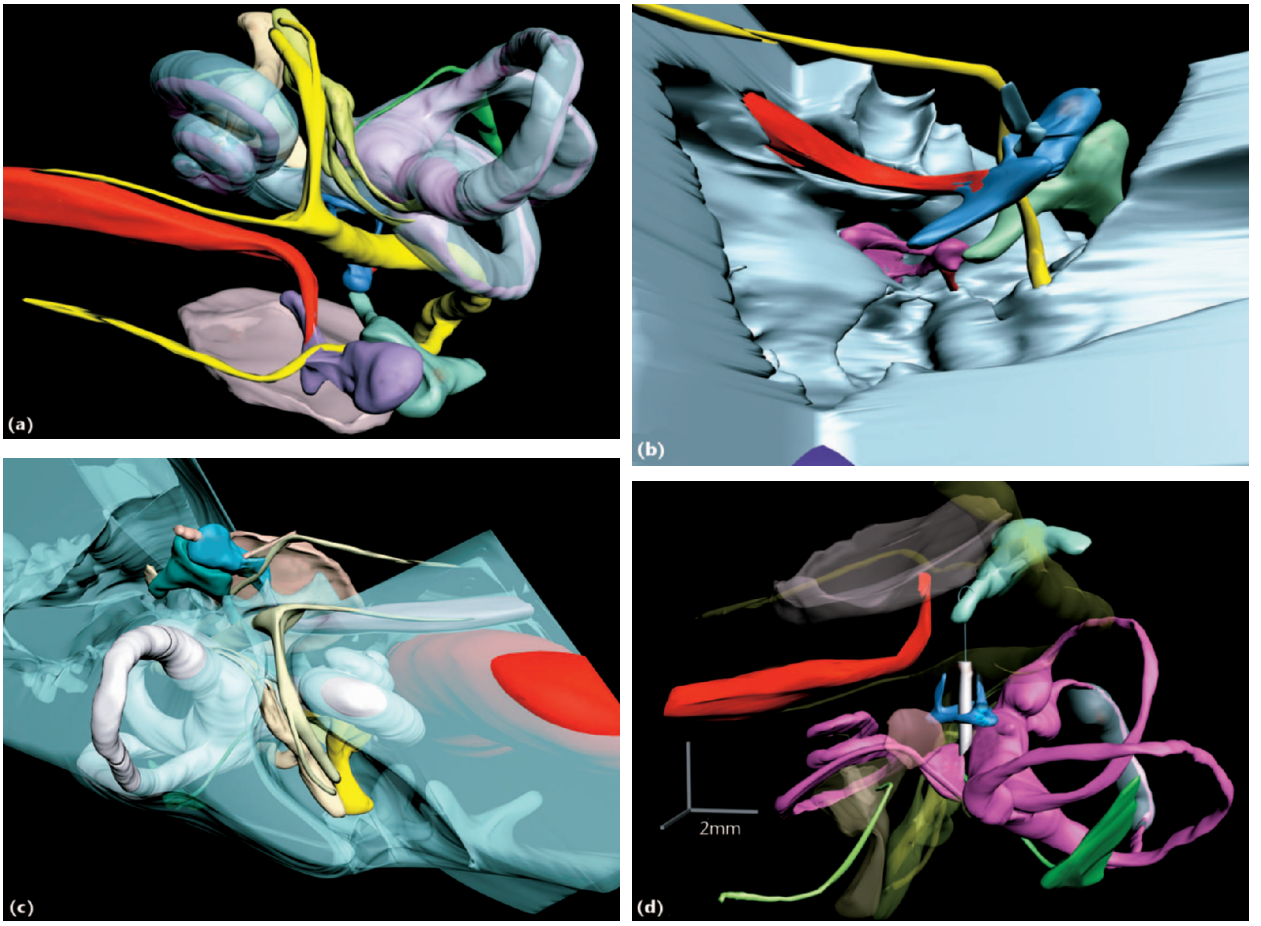


**Figure 5. 3D temporal bone reconstruction. (a) Microanatomy of the middle and inner ear, superior aspect, (b) microanatomy of the posterior tympanum, (c) branches of vestibulocochlear nerve and facial nerve, superior aspect, and (d) 3D relationship among the utricle, saccule, and stapes footplate.**

channel stereopticon system, the VR4000 stereoscopic visualizing system, and a Spaceball 5000 six-degree-of-freedom 3D controller (Virtual Realities; www.vrealities.com/spaceball5000.html). The virtual laboratory gives the user the sensation of total immersion in a virtual environment of the complex temporal bone structure.

Using 3DG-S18 liquid crystal display (LCD) goggles or 3DG-L3 polarization glasses (Tianjin 3D Imaging Technique; www.tj3d.com), users can view the model and move within the fully stereoscopic 3D virtual environment from the desktop or a large screen (see Figure 7) Using the Spaceball 5000's force-feedback device, users can easily move or rotate the 3D model by gently pushing, pulling, or twisting. The Spaceball controller was designed to provide smooth and dynamic model manipulation because the greater the pressure applied, the faster the model moves or rotates. The setup lets users manipulate the model in real time and travel inside it to look at anatomic objects from an infinite number of viewpoints—essential for understanding complex 3D interrelationships. In particular, owing to motion parallax effects, the ability to render at interactive speeds dramatically improves depth perception.

Computer-generated temporal bone models aren't new, but we've created more accurate and detailed structures by using a new undecalcified temporal bone specimen process and thinner histological samples, and by manually defining the samples' contour edge points. Our methods make this model much more anatomically meaningful for otolaryngology research and applications because it provides realistic, interactive anatomic information with true stereoscopic visualization. Although the VR approaches we employed are typical of current ones, ours could have a profound impact on future otolaryngology learning, surgery, and study.

With the advancement of modern neuro-otology, additional tiny, hidden, or previously overlooked temporal bone structures are becoming more important, and present special challenges to today's otolaryngologists.[13,14]

A temporal bone microanatomy vir-

tual laboratory has far-reaching implications not only for otolaryngology residents studying ear anatomy, but also for researchers investigating existing problems, planning new surgical methods, and examining unsolved mysteries, such as the mechanism of sound conduction in the middle and inner ear. We're also investigating and developing virtual surgery and patient data integration; we believe that more research applications will follow.


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## References


1. R.A. Nelson, *Temporal Bone Dissection Manual*, 2nd ed., House Ear Inst., 1991.
2. N.H. Blevins, R.K. Jackler, and C. Gralapp, *Temporal Bone Dissector*, Mosby, 1998.
3. M. Agus et al., "A Multiprocessor Decoupled System for the Simulation of Temporal Bone Surgery," *Computing and Visualization in Science*, vol. 5, no. 1, 2002, pp. 35–43.
4. J. Bryan, *A Virtual Temporal Bone Dissection Simulator*, master's thesis, Dept. Computer and Information Science, Ohio State Univ., 2001.
5. J. Bryan et al., "Virtual Temporal Bone Dissection: A Case Study," *Proc. IEEE Visualization 2001*, IEEE Press, 2001, pp. 497–500.
6. T.S. Karhuketo et al., "Virtual Endoscopy Imaging of the Middle Ear Cavity and Ossicles," *European Archives of Otorhinolaryngology*, vol. 259, no. 2, 2002, pp. 77–83.
7. C. Reisser et al., "Anatomy of the Temporal Bone: Detailed Three-Dimensional Display Based on Image Data from High-Resolution Helical CT: A Preliminary Report," *Am. J. Otolaryngology*, vol. 17, no. 3, 1996, pp. 473–479.
8. G. Wiet et al., "Virtual Temporal Bone Dissection Simulation," *Proc. Medicine Meets Virtual Reality 2000* (MMVR 00), J.D. Westwood, ed., IOS Press, 2000, pp. 378–384.
9. T. Harada, S. Ishii, and N. Tayama, "Three-Dimensional Reconstruction of the Temporal Bone from Histologic Sections," *Archives Otolaryngology—Head & Neck Surgery*, vol. 114, no. 10, 1988, pp. 1139–1142.
10. T.P. Mason et al., "Virtual Temporal Bone: Creation and Application of a New Computer-based Teaching Tool," *Archives Otolaryngology—Head & Neck Surgery*, vol. 122, no. 2, 2000, pp. 168–73.
11. C. Lutz et al., "Three-Dimensional Computer Reconstruction of a Temporal Bone," *Archives Otolaryngology—Head & Neck Surgery*, vol. 101, no. 5, 1989, pp. 522–526.
12. S.J. Ferguson, J.T. Bryant, and K. Ito, "Three-Dimensional Computational Reconstruction of Mixed Anatomical Tissues Following Histological Preparation," *Medical Eng. Physics*, vol. 21, no. 2, 1999, pp. 111–117.
13. D.D. Backous et al, "Relationship of the Utriculus and Sacculus to the Stapes Footplate: Anatomic Implications for Sound- and/or Pressure-Induced Otolith Activation," *Ann. Otology, Rhinology, and Laryngology*, vol. 108, no. 6, 1999, pp. 548–553.
14. H. Takahashi and I. Sando, "Three-Dimensional Surgical Anatomy for Stapes Surgery Computer-Aided Reconstruction and Measurement," *Laryngoscope*, vol. 102, no. 10, 1992, pp. 1159–1164.


**Figure 6. Temporal bone microanatomy virtual laboratory. Using a Spaceball 3D controller, a user manipulates the 3D model in real time.**

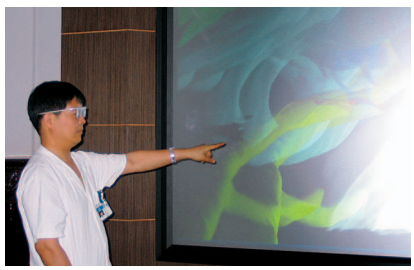

**Figure 7. Temporal bone microanatomy virtual laboratory. A user observes the stereo structures using a large screen and a two-channel stereopticon system.**


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