Otology & Neurotology
30:484–487 © 2009, Otology & Neurotology, Inc.

The Visible Ear Simulator: A Public PC Application for GPU-Accelerated Haptic 3D Simulation of Ear Surgery Based on the Visible Ear Data

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Background: Existing virtual simulators for middle ear surgery are based on 3-dimensional (3D) models from computed tomographic or magnetic resonance imaging data in which image quality is limited by the lack of detail (maximum, ~50 voxels/mm^3), natural color, and texture of the source material.

Virtual training often requires the purchase of a program, a customized computer, and expensive peripherals dedicated exclusively to this purpose.

Materials and Methods: The Visible Ear freeware library of digital images from a fresh-frozen human temporal bone was segmented, and real-time volume rendered as a 3D model of high-fidelity, true color, and great anatomic detail and realism of the surgically relevant structures. A haptic drilling model was developed for surgical interaction with the 3D model.

Results: Realistic visualization in high-fidelity (~125 voxels/mm^3) and true color, 2D, or optional anaglyph stereoscopic 3D was achieved on a standard Core 2 Duo personal computer with a GeForce 8,800 GTX graphics card, and surgical interaction was provided through a relatively inexpensive (~$2,500) Phantom Omni haptic 3D pointing device.

Conclusion: This prototype is published for download (~120 MB) as freeware at http://www.alexandra.dk/ves/index.htm.

With increasing personal computer performance, future versions may include enhanced resolution (up to 8,000 voxels/mm^3) and realistic interaction with deformable soft tissue components such as skin, tympanic membrane, dura, and cholesteatomas—features some of which are not possible with computed tomographic–/magnetic resonance imaging–based systems.

Key Words: Surgical simulation—Temporal bone—Virtual model.

Otol Neurotol **30:**484–487, 2009.

In preparation for ear surgery, students need to rehearse surgical anatomy, navigation, and drilling techniques in a complex anatomic environment. Because human temporal bones for drilling exercises are increasingly hard to provide, recent alternatives such as plastic temporal bones and computerized virtual interactive models have evolved.

Existing interactive virtual simulators for middle ear surgery are based on 3-dimensional (3D) models derived from clinical computed tomographic (CT) or magnetic resonance imaging (MRI) data (1–9) in which the natural colors and textures of the tissues are missing, and some of the smaller soft tissue components are poorly visualized. Moreover, image quality is depending on the lateral resolution of these imaging techniques, which has limited the detail of the 3D reconstructions to a maximum of 8 to 25 voxels/mm^3 (1–9; voxels are volumetric 3D units equivalent to 2D pixels). In addition to the provision of simulator software, virtual training often requires the purchase of expensive hardware such as a simulator platform with integrated haptic devices, stereoscopic eyepieces, mirror projection screens, foot switch, and a customized computer dedicated exclusively to this purpose (1–5,7–9). This may potentially limit the dissemination and benefits of ear surgical simulation and training technologies on a global scale.

The Visible Ear public image library (10) that was previously used for an anatomic interactive 3D surface model of the ear (11) contains high-fidelity cryosectional images of a normal human temporal bone in a surgically relevant volume. These data offer a potential basis for generating volumetric models of up to 8,000 voxels/mm^3 in (nearly) natural color. With current improvements in the performances of central processing units and 3D graphics cards, the first use of such data for realistic

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This study was supported by The Research Council at Rigshospitalet, the University of Copenhagen; the Alexandra Institute, and the Oticon Foundation.

surgical simulation on a high-end personal computer (PC) platform is possible.

This article presents a public Visible Ear Simulator (VES) beta version designed for use on a PC with a GeForce 8,800 GTX graphics card (or better) that aims to balance high quality in visual and haptic performance with low hardware cost and maximum user convenience.

MATERIALS AND METHODS

The public Visible Ear digital image library is based on a fresh-frozen human temporal bone from an 85-year-old woman with no history of previous ear disease. The bone, which had been donated to the Department of Anatomy, University of Copenhagen, was cryosectioned serially in the axial plane at a thickness of 25 μm, and digital images of the 12 × 20-cm block surface were recorded at 50- to 100-μm increments with a LightPhase (www.phaseone.com) single-shot camera back attachment on a Hasselblad 553 ELX camera (www.hasselblad.com). A total of 605 RGB 24-bit images of 3,056 × 2,032 pixels each were brought into registration with custom-made software by the application of a "least square best fit" algorithm of the vertical fiducial markers embedded inside the tissue block, cropped to display a constant area of 15.4 × 9.7 cm., and re-sampled to 3,078 × 1,942 pixels at a final resolution of 50 μm/pixel.

Twenty-eight anatomic structures of interest were segmented manually in Adobe Photoshop 7.0 (Adobe Systems Inc., San Jose, CA, USA). Precision and speed were enhanced by the use of semiautomated selection tools on a Wacom PL-400 digitizer screen (www.wacom.com).

The bone segment for drilling and the reference segments for navigation, including malleus, incus and stapes, dura, drum, facial nerve, and central nervous system (cerebrospinal fluid + brain + cerebellum + brainstem together) were all volume rendered in high fidelity and with great anatomic detail and realism using advanced GPU ray-casting. This technique enabled the inclusion of user-controlled transparency, shadowing, tinting, and visibility functions for all the relevant anatomic structures. Real-time renderings of the anatomy and the surgical instruments were achieved by combining ray-casting and standard rasterization.

A haptic drilling model was developed using volumetric techniques (12). Special attention was aimed at creating a force feedback function with a realistic "feel" even on a low-power Phantom Omni haptic device.

RESULTS

The simulator will install on any newer PC with Windows XP or Windows Vista an NVIDIA GeForce 8,800 GTX graphics card (or better, e.g., GF 280 GTX) and a Phantom Omni haptic device installed, registered, and calibrated according to the instructions available at the download homepage. This PC need not be reserved exclusively for simulator purposes but may be used for any other home or office activity when the simulator is not running. Nevertheless, visualization in high fidelity (~125 voxels/mm^3) and true color, 2D, or optional anaglyph stereoscopic 3D and realistic real-time haptic interaction is achieved (Fig. 1).

A full-screen interface of 1,024 × 768 pixels or better offers a triptych display with a left "tools" panel, a right "visual settings" panel, and a central surgical "workspace" of the 3D temporal bone and drills (Fig. 2).

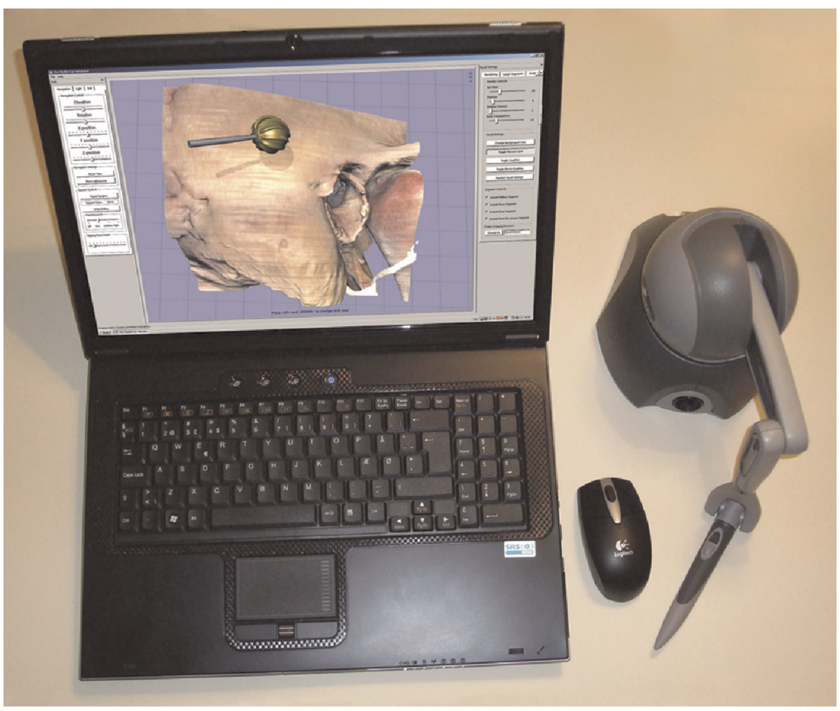

FIG. 1. Simulator setup. Portable PC with GeForce 9,800 M GTX graphics card and Windows Vista 32 bit, mouse, and Phantom Omni haptic device. Central workspace with temporal bone and 7-mm sharp drill bit ready for drilling in haptic mode.

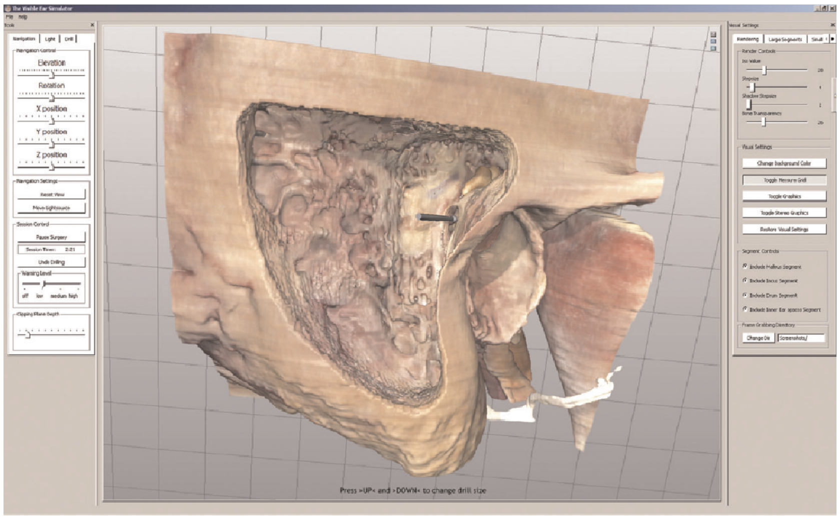

FIG. 2. Triptych display with mastoidectomy specimen. Note the transparency where the bone was thinned over the lateral semicircular canal and the vertical part of the facial nerve. A 1-mm diamond drill bit is seen inside the posterior tympanotomy.

In initial "mouse mode," the "tools" panel controls are operated with the PC mouse to start a drilling session, load a previously saved "game," save the current session for later use, pause or exit surgery, or adjust the virtual light source, calibrate the effectiveness of the drills and the "weight" of the drill hand piece. The "Undo Drilling" button will step back the surgical session by 1 second per click when needed. The "Warning level" button may alter the threshold for popup messages of unwanted drill contacts with embedded soft tissue elements. A session timer keeps track of the duration of the current session.

In the "visual settings" panel, fundamental rendering options are calibrated with sliders as suggested and explained in detail in the online manual. A "bone transparency" slider is included to adjust the specially designed "natural" transparency function, which renders the bone segment transparent through a limited depth from the drilled surface while leaving bony voxels at deeper levels opaque. If needed, these settings may be restored to default values by a single click. Among other functions, the image may be toggled to anaglyph red/blue stereoscopic mode, where the user may experience true 3D vision through red/blue glasses at the cost of some color reduction. The background color may be changed, and in the "Segments" sections, the transparency and color tinting of the individual anatomic structures can be changed or turned off. If needed, selected structures such as the drum, incus, malleus, and membranous labyrinth may be turned off to avoid irrelevant popup warnings during, for example, labyrinthectomy.

In the central workspace, the position, rotation, and magnification of the temporal bone model may be controlled with the PC mouse buttons and wheel by click-and-drag motions.

When the "space" bar is pressed, the simulator toggles into "haptic mode," the arrow cursor is replaced by a hand symbol, and the model can be moved around similarly by pen movements and buttons on the haptic device.

In "haptic mode," the "Ctrl" button activates a drill selection pie menu from which sharp and fine drills ranging from 0.5 to 7 mm may be activated. When a drill head has been selected, the model may be explored haptically by moving the pen device and drilled by depressing the pen button. When the drill is spinning, the haptic hand piece will vibrate. When the bone is engaged, vibrations increase, and if a sound card is present, drilling sounds are heard.

Keyboard "quick buttons" include functions for changing the size of the drill, for adjusting the hand piece to a comfortable position, and for saving 3.4-MB color Bitmap snapshots of the central workspace to a default directory "Screenshots" for use in instructional papers or presentations.

DISCUSSION AND CONCLUSION

The design of the present simulator reflects a number of choices made in the developmental process.

Computed tomographic/MRI data are easy to obtain and lend itself to fast semiautomatic 3D rendering of large bony volumes. Moreover, these imaging sources offer the possible rendering of custom reconstructions for drilling rehearsals in preparation for planned surgery (2,3,7). However, the maximum resolution of clinical imaging techniques limits the detail of the 3D reconstruction (to a crude 8–25 voxels/mm^3) and the accuracy of the segmentation whether manual or automatic. Soft tissue segments are generally less well defined, and artificial color information must be added subsequently because the original data contain only gray-scale information. In case of, for example, an aberrant or branching facial nerve, where surgical precautions would be most important, a preoperative 3D reconstruction based on clinical CT data could easily fail to demonstrate the abnormality. In such cases, a virtual surgical preview would be of little value to the patient and surgeon. Even with the use of experimental micro-CT and high Tesla MRI on donated postmortem specimens, the 50-voxels/mm^3 quality of the best 3D reconstruction is inferior to that of a histologic/microanatomic model (13). Nevertheless, we are currently developing a CT import function for users who want an optional low-resolution interaction with the bony segment of custom specimens.

At this time, the VES offers just a single normal human specimen. However, a standard PC can handle this model in real time at 125 voxels/mm^3, and as PC performance develops, the resolution may be increased to 8,000 voxels/mm^3. The future inclusion of additional temporal bones similarly processed will require only another few days of simulator programming, but the time needed to segment such a new set of data is 100 to 150 hours for the bony segments and a total of 450 hours for an all-inclusive "Visible Ear"–type registration of hard and soft structures. Another option could be the future modification of the Visible Ear specimen by the introduction of drum perforations, cholesteatomas, or tumors directly into the segmented 3D model. All the soft tissue components such as the dura, the drum, and the skin of the ear canal are fully represented in the Visible Ear data. In the present simulator, these soft segments appear only as reference points for the bony drilling activity, but future versions may include them as deformable surface renderings that can be explored, incised, and deflected with suitable haptic virtual instruments.

The virtual illusion will most likely never become perfect, but "immersion" and realism may be enhanced by the use of, for example, foot switch, mirror projection screens to align the haptic device with the users' line of vision, binocular eyepieces for stereoscopic vision under "surgical microscopic" conditions, bilateral haptic devices for combined drilling and suctioning of virtual blood, and osseous debris. Different options were preferred in the VES to keep the user costs low, and because the control of, for example, the drilling action by the use of buttons on the haptic hand piece was considered to be acceptable in comparison with a foot switch, red/blue glasses for stereoscopic screen vision were a minor drawback compared with microscope eyepieces and so on. Moreover, a simple setup with just 1 haptic device connected to the PC enhances user convenience and may even shift the simulator from an expensive institutional all-office application toward a combined home/office device. New haptic devices for leisure PC gaming will most likely reduce the cost of a suitable drilling device to US $200 in the near future.

Learning metrics are scheduled for coming versions, and studies on the possible effect of added virtual training on the learning curve of surgical trainees are currently underway. However, the present version contains no surgical instructions and no test functions for recording the effect of training activities. In this respect, the VES is, at this time, similar to any cadaver temporal bone. However, although originally conceived simply as a poor substitute for donated human temporal bones, the VES offers some features, which are exclusive to this type of training technology, such as save/restore options, transparency functions, undo functions, popup warnings, PC projection output for plenum sessions, and, perhaps, future "haptic tutorials" in which the student may experience pen-guided playback haptic drilling sessions recorded by skilled surgeons.

The VES is offered for worldwide free download at the authors' Web site (http://www.alexandra.dk/ves/index.htm) together with a PDF manual for installing and drilling.

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