A Three-dimensional Interactive Virtual Dissection Model to Simulate Transpetrous Surgical Avenues

Antonio Bernardo, M.D.
Division of Neurological Surgery and Neurosurgery Research Laboratory, Barrow Neurological Institute, St. Joseph's Hospital and Medical Center, Phoenix, Arizona

Mark C. Preul, M.D.
Division of Neurological Surgery and Neurosurgery Research Laboratory, Barrow Neurological Institute, St. Joseph's Hospital and Medical Center, Phoenix, Arizona

Joseph M. Zabramski, M.D.
Division of Neurological Surgery and Neurosurgery Research Laboratory, Barrow Neurological Institute, St. Joseph's Hospital and Medical Center, Phoenix, Arizona

Robert F. Spetzler, M.D.
Division of Neurological Surgery and Neurosurgery Research Laboratory, Barrow Neurological Institute, St. Joseph's Hospital and Medical Center, Phoenix, Arizona

Reprint requests:
Robert F. Spetzler, M.D., c/o Neuroscience Publications, Barrow Neurological Institute, 350 West Thomas Road, Phoenix, AZ 85013-4496.
Email: neuropub@chw.edu.

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OBJECTIVE: This project involves the development of a three-dimensional surgical simulator called *interactive virtual dissection*, which is designed to teach surgeons the visuospatial skills required to navigate through a transpetrosal approach.

METHODS: A robotically controlled microscope is used for surgical planning and data collection. The spatial anatomic data are recorded from sequentially deeper cadaveric head dissections as a series of superimposed anatomic pictures in stereoscopic digital format. The sequential series of images are then merged to form the final virtual representation.

RESULTS: The current three-dimensional virtual reality simulator allows the user to drill the petrous bone progressively deeper and to identify crucial structures much like an experienced surgeon drilling the petrous bone. The program allows surgeons and trainees to manipulate the virtual "surgical field" by interacting with the surgical anatomy. The interactive system functions on a desktop computer.

CONCLUSION: The ability to visualize and understand anatomic spatial relationships is crucial in surgical planning, as is a surgeon's confidence in performing the surgery. The virtual reality simulator does not replace the need for practicing surgery on cadavers. However, it is designed to facilitate, via stereoscopic projection, learning how to manipulate a drill in complicated or unfamiliar surgical approaches (e.g., a transpetrosal approach).

KEY WORDS: Computer-aided learning, Neurosurgical education, Surgical anatomy, Surgical simulation, Virtual reality

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Most neurosurgical approaches require dexterity with surgical instrumentation, specifically bone removal instruments, often through restricted corridors that contain vital structures in the surrounding area. This aspect of surgery demands that surgeons be proficient not only with the tools but also with the complex anatomy to be negotiated. For example, the development of a sense of the anatomic relationships between neural and vascular structures encased by bone is critical and requires practice. Although neurosurgeons have learned their craft in an apprentice milieu, and for the near future will continue to learn it in that manner, the current medicolegal climate suggests that early repetitions and the mistakes that undoubtedly will be made during them should not be undertaken at the patient's expense. In addition, many patients now insist that the attending surgeon perform the complete operation and that assistants, such as residents, play a relatively minor role.

These limitations, coupled with those imposed by the inherent perspective constraints of two-dimensional images and noninteractive three-dimensional (3-D) images, seem to argue for neurosurgical educational opportunities that can provide a convenient, satisfactory, simulated, interactive, 3-D practice experience. We describe a project, called *interactive virtual dissection* (IVD), that integrates exquisite cadaveric dissections, 3-D visualization, virtual reality, and computerized simulation for training of surgical procedures and visuospatial skills. In this first application, IVD focuses on simulating the drilling of the petrous bone, a common cranial base surgical avenue associated with complex anatomy.

IVD PRODUCTION

The IVD system architecture consists of 1) generation of data from progressive surgical exposures; 2) acquisition of digital and stereoscopic anatomic data; 3) image reconstruction, segmentation, and merging, leading to an accurate 3-D anatomic model; and 4) a virtual reality surgical simulator that uses the anatomic model to simulate dynamic behavior.

Data Generation

A dedicated dissection working station has been designed to collect digital anatomic and surgical data generated from perfused, arterial and venous, colored silicone-injected cadaveric dissections. The dissection is performed in sequential steps that reproduce an actual surgical procedure.

Data Collection

The data collected are digital and stereoscopic. The robotic voice-controlled microscope system, with special control software, digitally encoded zoom and focus functions, and proprietary developmental software, defines the spatial coordinates numerically and is used to register the position of the microscope in space (Zeiss MKM carrier with OPMI neurosurgical microscope; Carl Zeiss Surgical, Inc., Thornwood, NY). The navigational system (Carl Zeiss Surgical, Inc.) and the headholder are correlated so that the system can pinpoint the exact position of the head in space. It is crucial that the microscope and the cadaver head do not change position with respect to each other.

An optimal surgical position is selected at the beginning of the procedure and is used throughout the session. Selecting this surgical position is fundamental to the process. The most important anatomic landmarks must be included throughout the entire procedure. Once a surgical position has been selected, the spatial coordinates and zoom and focal values are recorded with the microscope control software. This preset and recorded surgical position is used as the starting point to acquire digital stereoscopic pictures throughout the entire dissection. The microscope control software allows the working trajectory, inclination, and zoom and focal values to be changed. It restores the microscope to the initial preset surgical position and corrects the zoom setting and microscope trajectory to ensure anatomically correct representations at all times. When digital images are obtained, the spatial coordinates and focal/zoom parameters must be the same to obtain digital data that superimpose.

To create a realistic surgical experience in a transpetrous route, for example, as a mastoidectomy progresses, it is important to proceed through the removal of the bone in a systematic, smooth, stepwise method, maintaining a uniform depth throughout the dissection. Avoiding "digging holes" with the drill allows a uniform reproduction of the surgical bony anatomy throughout the procedure. A Midas Rex III (Medtronic Midas Rex, Fort Worth, TX) power tool system is used for bone dissection.

Digital images are collected with two digital cameras (Canon EOS D30 microscope-mounted; Canon, Inc., Tokyo, Japan). Alternatively, a Zeiss MediLive 3-D video system with Advanced Digital Camera Control Unit (Carl Zeiss, Inc.) is connected directly to a graphics workstation, mounted on both arms of the microscope, and operated with a synchronized remote shutter from the graphics workstations. Each camera is attached to a digital monitor (Sony Corp., Tokyo, Japan) to ensure image alignment and satisfactory collection of the anatomic information in near real time. This setup permits a continuous stream of digital data from the production unit to the processing workstations.

Data Processing

By use of two graphics workstations with standard, commercially available graphics and 3-D image manipulation software, each pair of photographs is interlaced (i.e., left and right) to generate the stereoscopic format. The digital data are then processed into multiple stereoscopic layers and arranged in sequential surgical order. The program allows the user to simulate "drilling" away each single layer to reveal the next one.

The program uses a 3-D computerized reproduction of the drill. The drill size and shape can be selected to match the particular surgical step, as during an actual surgical scenario. For instance, a small drill with a diamond tip can be used for fine, delicate drilling, such as around a nerve or the labyrinth. A bigger bit can be used for gross dissection, such as a superficial mastoidectomy (*Fig. 1*). Drill sound reproduction accompanies the simulation. An ocular-viewed display mimics the view through the surgical microscope.

APPLICATIONS OF VIRTUAL REALITY TECHNOLOGY

Neurosurgical residents acquire most of their surgical skills in the operating room (2, 8, 10). There may never be a replacement for the live situation of the operating room as the final environment for learning to perform operations (3). In many ways, however, the operating room is not the ideal classroom for learning or refining surgical skill. The operating room is often a very stressful environment. The progress or sequence of the operation can seldom be altered to satisfy or expand educational goals. Surgical steps cannot be repeated, and the patient cannot be reassembled to start over if failure occurs.

Dissection laboratories also have limitations. They may not be conveniently available to students. They are costly to run and require specially trained personnel and procedures. The availability of optimal cadaver specimens is often limited. The educational value of surgical and anatomic textbooks is insufficient in terms of supporting complex visual learning objectives, because a two-dimensional environment must be extrapolated to a 3-D environment (e.g., surgical exposures are often oriented upside down and at an angle compared with anatomic views) (4).

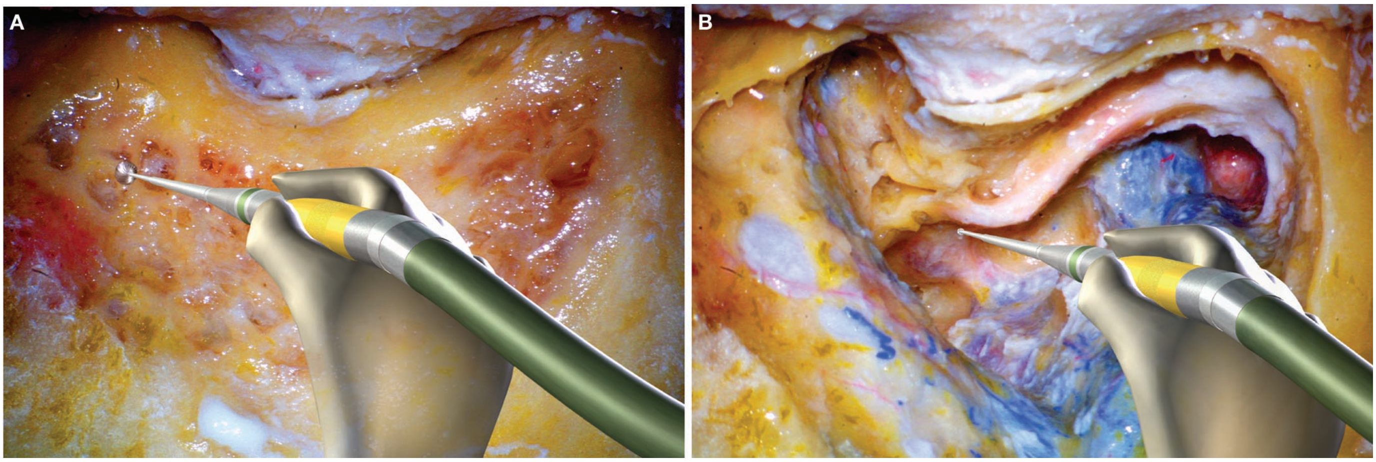

FIGURE 1. A *and* B, *demonstrations of interactive virtual dissection surgical simulation. The program allows the user to simulate "drilling" away each layer to reveal the next one. The program uses a 3-D computerized reproduction of the drill, allowing the selection of the drill size and shape for each surgical step as in a real surgical scenario.*

The number of hands-on surgical education courses has increased, but satisfactory in-depth teaching is limited. Most such courses cannot provide attendees enough time or step-by-step instruction to actually become proficient at a given procedure. Frequently, a course must be taken several times before the neurosurgeon is confident enough to perform a new procedure in the operating room. These courses may be able to accommodate only a limited number of registrants. They also may be expensive.

Simulations in Training and Education

The concept of interactive computerized visualization opens new realms in the educational process (1). Stereoscopy or 3-D presentation helps to improve trainees' conceptual grasp of complex anatomy and their understanding of visuospatial tasks (4). Virtual reality technology permits computed 3-D images obtained from cadaveric dissections to be manipulated conveniently with an intuitive immediacy similar to that of real objects.

The usefulness of training simulations has been recognized for some time (9). For example, simulations are well known for their roles in civilian and military pilot (12), tank crew (11), and astronaut training. Simulation in medical education has been undertaken in a variety of settings (3). Paramedical personnel are taught triage and assessment skills with this technique. Advanced trauma life support and advanced cardiac life support courses rely on simulated scenarios to teach and test skills. Screen- and mannequin-based simulators have been used in anesthesia training to ensure that clinicians are exposed to unusual situations, such as malignant hyperthermia, anaphylaxis, and cardiac ischemia, that they would not otherwise experience routinely. The cost-effective use of simulators has demonstrated the usefulness of real-time simulation as a training tool.

Surgical Simulation

Surgical simulation refers to a human-computer interface that facilitates highly interactive visualization and control of computer-generated 3-D scenes and their related components with sufficient detail and speed to evoke a sensorial experience similar to that of real experience. The ability to manipulate 3-D models and to view anatomy from different perspectives is especially useful in petrous bone surgery, in which preoperative planning and port placement often dictate and restrict the angle of approach (*Fig. 2*). In this instance, IVD is meant to facilitate learning how to manipulate a transpetrosal approach or other cranial base surgical procedures efficiently by allowing the student to practice surgical skills in a 3-D simulation (*Fig. 3*).

Various groups have attempted to develop sophisticated virtual reality systems that elegantly simulate surgical proce-

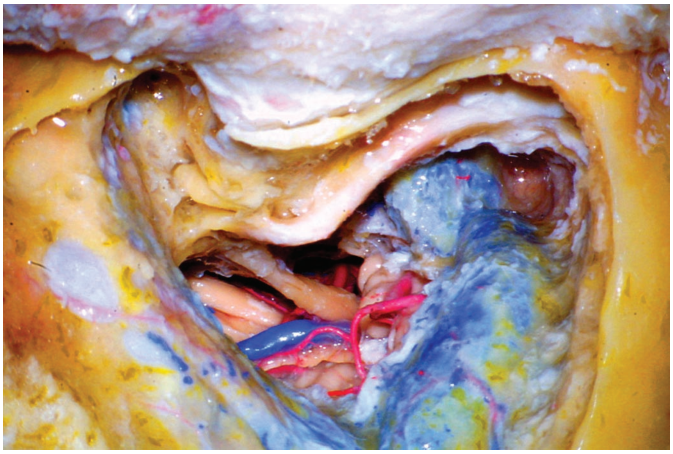

FIGURE 2. *Cerebellopontine exposure as seen at the end of the IVD translabyrinthine surgical exposure.*

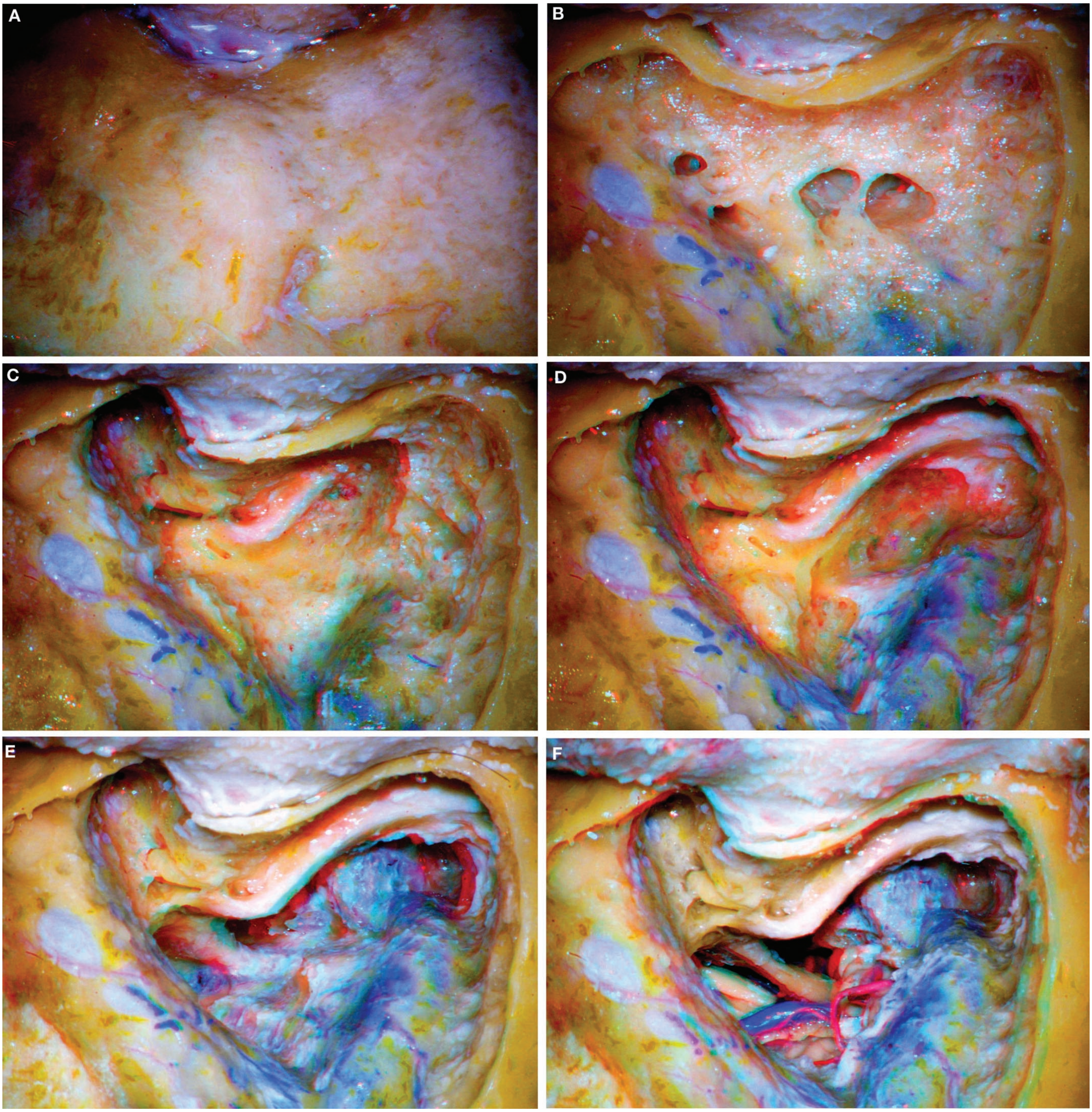

FIGURE 3. *3-D demonstration of the IVD model: the simulator allows the user to drill the petrous bone progressively and to identify crucial structures in the manner of an experienced surgeon.* A, *the cortex over the mastoid bone is removed with a large cutting burr.* B, *the sigmoid sinus is exposed posteriorly and inferiorly. The middle fossa dura is exposed superiorly.* C, *after the antrum has been opened, the facial nerve and the horizontal semicircular canal are identified.* D, *with a smaller burr, the facial nerve is skeletonized distally to the stylomastoid foramen.* E, *the labyrinth is removed, and the dura of the internal auditory canal is exposed.* F, *the dura is incised, revealing the VIIth and Vth cranial nerves and the anteroinferior cerebellar artery in the cerebellopontine angle.*

dures in a virtual environment. Initial work and results with virtual surgical simulators are encouraging, although problems remain in faithfully reproducing generalized anatomic haptic feedback (5–7). Most simulators produce a 3-D experience, but thus far, these systems have proved to be costly because they require complex computer hardware and software. Furthermore, they are not easily accessible or convenient. Currently, our IVD simulation model can neither calculate contact forces nor generate virtual tissue displacements. The virtual dissection is not simulated with a physics-based model reconstructed from computerized data. Instead, the IVD is uniquely designed with real anatomic data collected from cadaveric specimens and therefore generates a realistic visual experience (*Figs. 4* and *5*).

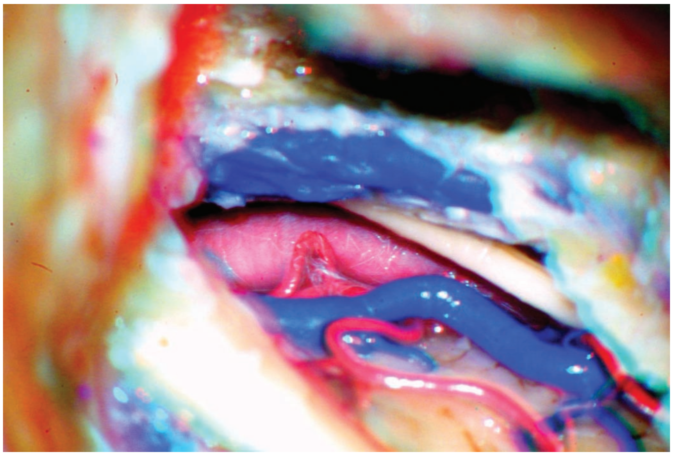

FIGURE 5. *3-D demonstration of exposure of the midbasilar artery at the end of an IVD transcochlear surgical approach after transposition of the facial nerve.*

Feedback and Assessment of Performance Using Virtual Reality

Optimally, virtual reality systems such as IVD should include measures to track the user's performance and the ability to provide feedback without requiring the presence of an instructor. IVD now consists of an interactive 3-D format without haptic devices. The user can use the simulator on a desktop computer and monitor with no need for special software. Easily acquired, inexpensive stereoscopic shutter glasses are used for stereoscopic image perception. A more sophisticated and comprehensive version under development will include the use of haptic technology that creates a sense of touch in a multimodal medium and will allow manipulation of other anatomic structures.

Future Directions

In this iteration, our system models surgical manipulation and navigation through anatomy as it appears to a surgeon performing petrous bone surgery. Currently, the program allows a surgeon or trainee to manipulate the virtual surgical field by actively interacting with the surgical anatomy through a bone-drilling exercise. Simulations in production include other frequently applied cranial base surgical interventions, such as anterior and posterior clinoidectomy, a far-lateral approach, and transfacial surgical avenues. A more realistic microscope ocular-like display is also being added.

A neurosurgically oriented dissection laboratory environment is the ideal training arena for neurosurgical residents and surgeons. There is no substitute for diligent practice of these techniques in the laboratory setting. Adequate preoperative training and rehearsal of complex approaches to the cranial base require that such exercises take place under conditions that simulate an actual operation as closely as possible. The IVD simulator will allow surgeons and residents to practice procedures in an environment in which mistakes have no dire consequences, lowering the risk associated with training on human patients and establishing standards and optimization of specific procedures.

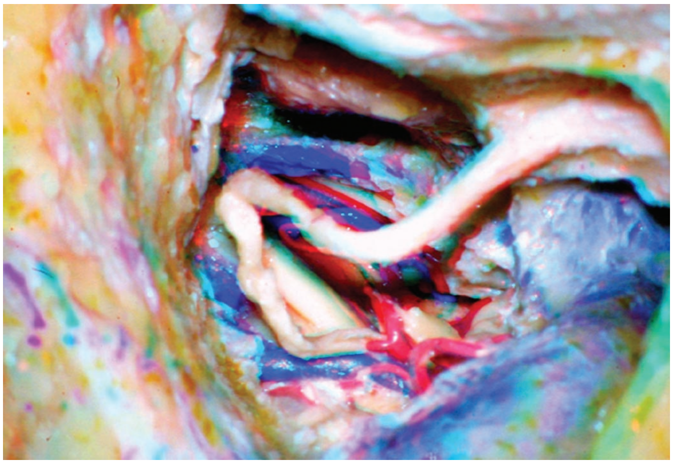

FIGURE 4. *3-D demonstration of an IVD transcochlear surgical approach. The facial nerve is completely free and is ready to be transposed.*

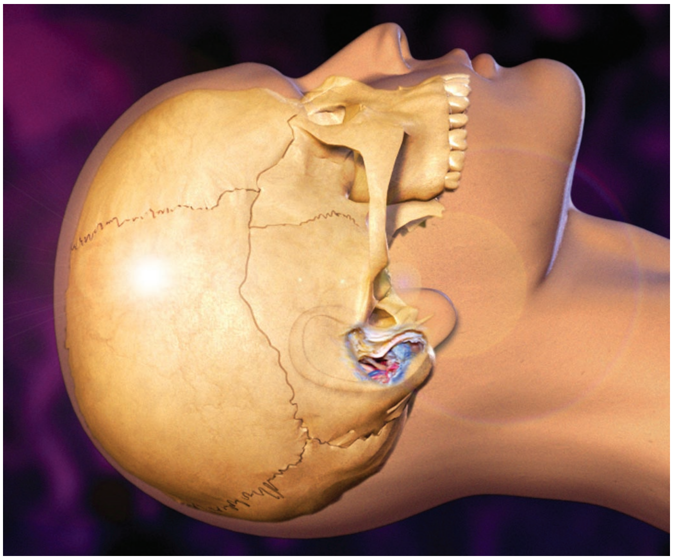

FIGURE 6. *Simulated surgical position for an IVD transcochlear approach.*

Great potential for revolutionary innovation in the teaching and practice of surgical anatomy lies in dynamic, fully immersive, multisensory fusion of real and virtual information data streams (1). Virtual reality technology now permits the computed 3-D images obtained from cadaveric dissections to be manipulated with an intuitive immediacy similar to that of real objects and by engaging other senses, such as touch and hearing, to enrich the simulation (*Fig. 6*).

Such a system, however, will not replace the realism of actual painstaking experience gained from cadaveric dissections. Furthermore, virtual reality is not yet able to create the stress associated with actual surgery or the concomitant physiological sequelae and necessary interventions that accompany, for example, major hemorrhage or dangerous brain swelling, just as virtual reality cannot substitute for the battle-hardened experience of an elite M1A2 Abrams tank commander. Although the training of neurosurgeons should not transform them into "computer surgeons," virtual reality technology, such as IVD, can be used to significantly enhance the educational process.

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COMMENTS

The authors collected stereoscopic images during transpetrosal bone drilling in cadavers, using a neuronavigational microscope. The sequence of images can be played back and forth by a virtual drill on a desktop computer screen. This is the beginning of an exciting avenue in neurosurgical teaching and training.

Two essential aspects of virtual neurosurgery are still missing: 1) virtual dissection tools, and 2) haptics. Virtual tools allow the surgeon to navigate, visualize, endoscope, displace, cut, and remove segmented structures in any orientation in three-dimensional virtual anatomy. Haptics allows feedback sensation on the screen, as a needle holder for arterial anastomoses or a dentist's drill is moved through a force-feedback device that conveys tissue resistance to the surgeon's hands. The imaging described here does not match the delicate interplay between the tissues and the surgeon's instruments, hands, and eyes, but it will help to teach, demonstrate, and standardize neurosurgical approaches worldwide. Virtual neurosurgery is extremely expensive to develop, and the market is limited to the academic environment, but it is certainly a wave of the future.

Juha Jääskeläinen
Peter McL. Black
Boston, Massachusetts

The complex three-dimensional structures and intricate functions contained within the petrous temporal bone make it one of the most challenging surgical domains facing the modern neurosurgeon. Classically, apprentice neurosurgeons have trained in the anatomy, surgical approaches, structures, and anatomic relations of this area of the cranial base by conducting exercises in "temporal bone laboratories" using cadaveric specimens. In this article, Bernardo et al. provide a description of the initial development of a three-dimensional surgical simulation project, which they call *interactive virtual dissection*, citing the current medicolegal climate and the need for preoperative planning and rehearsal of operative procedures as the impetus for this endeavor. Their goal, as outlined in the article's introduction, is to achieve an interactive virtual reality environment in which the user can simulate training of surgical procedures while developing visuospatial skills specifically related to "transpetrous surgical avenues." To accomplish this, they use stereoscopically rendered images representing progressively deeper cadaveric dissections of the surgical anatomy of interest. The simulation is executed on a desktop computer; although the computer's specialized configuration is presumed to be modest, details are not given. The need for two digital cameras and two dedicated graphics workstations for initial image data acquisition and reconstruction is mentioned. The authors readily point out that their system is purely graphically based, and they make no attempt to model tissue biomechanical deformation characteristics according to physical criteria; thus, no haptic (i.e., tactile) feedback is provided. The authors report that there are plans for incorporation of this modality in later iterations.

This report represents a significant advancement in simulated petrous bone surgery since the work of Kuppersmith et al. (2), who reported in 1997 on the development of an augmented virtual reality temporal bone dissection simulator incorporating haptic feedback. Abe et al. (1) developed a simulator based on the stereolithographic generation of acrylic models of the region of surgical interest. Subsequent addition of detailed models of vasculature and other intracranial structures would be handmade. Zielinski and Sloniewski (3) improved on this modeling technique by reconstruction of the bony pyramid from 1-mm computed tomographic slices. This model was created in virtual reality markup language (VRML) so that it could be made available over the Internet.

Bernardo et al. have provided us with the beginnings of an elegant solution to simulated surgery of the petrous bone with concomitant opportunities for understanding and ultimately mastering its associated anatomy and anatomic relationships in a no-risk environment. Their use of readily available personal computer equipment for the execution of the simulation and use of inexpensive liquid crystal display stereoscopic glasses for viewing the surgery as it progresses should make this system easily accessible to most users. Haptic feedback is planned and, particularly with reference to drilling of bony structures, has been amply described in the literature on using articulated arm devices (with as many as six degrees of freedom), so it should not be difficult to integrate. This feedback represents an important addition to this system, as the recognition of vital labyrinthine structures is often first noted by tactile appreciation rather than by visual verification.

Mark A. Spicer
Los Angeles, California

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The authors have described what amounts to a kind of "flight simulator" for teaching a neurosurgical approach to the cranial base. This concept certainly has value when one considers that a neurosurgeon's individual development of expertise should not be "at the patient's expense." Although this system appears to have some significant limitations, it is an important step in the development of sophisticated educational tools for neurosurgery. I would echo some of the authors' cautionary statements in the article. Such a tool should not be viewed as a conduit for bringing complicated cranial base surgery to the neurosurgical "masses." For the very limited number of individuals who pursue serious training in this discipline and will actually practice a sufficient volume of cranial base surgery to be competent, such simulators may be a valuable tool as part of their education. As the authors point out, it will not be a substitute for adequate time spent in the cadaver dissection laboratory training one's brain and hands to become familiar with the complex three-dimensional neuroanatomic relationships. In addition, it will not be a replacement for the "apprenticeship" that must be spent with an accomplished cranial base surgeon to learn the nuances of the procedures. Nor will it be much assistance during the "combat training" phase of the surgeon's development, when battles are fought with bleeding, distorted anatomy, and postoperative complications. However, the work of these surgeons will help to improve our training process, and I look forward to future iterations of this type of training tool.

John Diaz Day
Pittsburgh, Pennsylvania

Computer-generated "surgical fields" have been rather primitive thus far, except to simulate simple surgery (usually endoscopic) on noncomplex tubular structures, such as the gut or the tracheobronchial tree, and defined systems, such as the orbit or the ventricular system. In this article, the authors do something that has generated hoots of derision from virtual reality purists when I have suggested it in the past: they are using stereoscopic video from actual surgical dissections (cadaver specimens) as "wallpaper" over which a simplistic computer-generated image can be superimposed. This reduces the necessity for massive computer horsepower. Digitized stereoscopic images of actual surgical fields could also be pulled from a computer disk library of images in future versions of simulators like this one.

A force feedback (haptic) interface is required for a surgical simulator to be really convincing. Even though this feature is cumbersome and expensive, the "feel" of tissue within the field cannot be added to the experience without it. In addition, the computer must know the location of a tool in space to accurately update an image display. But most digitizers are bulkier than the tool itself—especially microinstruments. Nonetheless, the system described in this article should improve the learning curve of neurosurgical trainees in their three-dimensional knowledge of petrous bone surgical anatomy. In addition, this system will be less expensive than cadaver heads and will not require a trip to the anatomy laboratory.

Ideally, a virtual surgical simulator should provide sensory input to all of our senses for a virtual experience that simulates real-life experience. In my opinion, the "gold standard" (and the most sophisticated virtual training system) is the flight simulator used by the military and large airline companies. The experience such devices provide is invaluable and almost lifelike. Pilots have been known to become tachycardic, hypertensive, and diaphoretic during simulated "emergencies"; they even argue with their "co-pilots." After a session in the simulator, encountering one emergency after another, most pilots are mentally and physically exhausted. In aircraft simulators, pilots can actually feel that they are in an aircraft. But I have yet to see a surgical simulator that makes me believe that I am in an operating room.

Patrick J. Kelly
New York, New York