NEW TECHNOLOGY

Virtual Reality in Neurosurgical Education: Part-task Ventriculostomy Simulation with Dynamic Visual and Haptic Feedback

G. Michael Lemole, Jr., M.D.

Department of Neurosurgery,
University of Illinois, Chicago,
Chicago, Illinois

P. Pat Banerjee, Ph.D.

Departments of Mechanical
and Industrial Engineering,
and Computer Science,
University of Illinois, Chicago,
Chicago, Illinois

Cristian Luciano, M.S.

Departments of Mechanical
and Industrial Engineering,
and Computer Science,
University of Illinois, Chicago,
Chicago, Illinois

Sergey Neckrysh, M.D.

Department of Neurosurgery,
University of Illinois, Chicago,
Chicago, Illinois

Fady T. Charbel, M.D.

Department of Neurosurgery,
University of Illinois, Chicago,
Chicago, Illinois

Reprint requests:
G. Michael Lemole, Jr., M.D.,
Department of Neurosurgery,
Section of Skull Base Neurosurgery,
University of Illinois, Chicago,
912 S Wood Street, M/C 799,
Chicago, IL 60612.
Email: mlemole@uic.edu

Received, July 1, 2006.

Accepted, February 24, 2007.

OBJECTIVE: Mastery of the neurosurgical skill set involves many hours of supervised intraoperative training. Convergence of political, economic, and social forces has limited neurosurgical resident operative exposure. There is need to develop realistic neurosurgical simulations that reproduce the operative experience, unrestricted by time and patient safety constraints. Computer-based, virtual reality platforms offer just such a possibility. The combination of virtual reality with dynamic, three-dimensional stereoscopic visualization, and haptic feedback technologies makes realistic procedural simulation possible. Most neurosurgical procedures can be conceptualized and segmented into critical task components, which can be simulated independently or in conjunction with other modules to recreate the experience of a complex neurosurgical procedure.

METHODS: We use the ImmersiveTouch (ImmersiveTouch, Inc., Chicago, IL) virtual reality platform, developed at the University of Illinois at Chicago, to simulate the task of ventriculostomy catheter placement as a proof-of-concept. Computed tomographic data are used to create a virtual anatomic volume.

RESULTS: Haptic feedback offers simulated resistance and relaxation with passage of a virtual three-dimensional ventriculostomy catheter through the brain parenchyma into the ventricle. A dynamic three-dimensional graphical interface renders changing visual perspective as the user's head moves. The simulation platform was found to have realistic visual, tactile, and handling characteristics, as assessed by neurosurgical faculty, residents, and medical students.

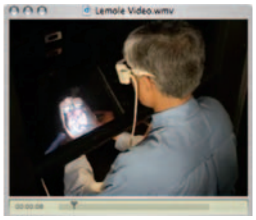
CONCLUSION: We have developed a realistic, haptics-based virtual reality simulator for neurosurgical education. Our first module recreates a critical component of the ventriculostomy placement task. This approach to task simulation can be assembled in a modular manner to reproduce entire neurosurgical procedures.

KEY WORDS: Graphics collocation, Haptic collocation, Simulator, Ventriculostomy, Virtual reality

Neurosurgery 61:142–149, 2007 DOI: 10.1227/01.NEU.0000255485.65450.49 www.neurosurgery-online.com

Neurosurgical education is a long, laborious process, requiring many years of directed, hands-on training. Traditionally, anatomic knowledge pertinent to a surgical procedure is first imparted through textbooks and atlases. More recently, computer-based images and animations have improved our ability to depict complex anatomic relationships (5, 14, 18, 42). Cadaveric dissection provides the most realistic interaction with human anatomy outside of the operating room. Unfortunately, the cost and labor involved in creating and maintaining such a facility are not within the reach of all training programs (43).

The proverbial operative and procedural suite has long been the mainstay for teaching surgeons-in-training. The patient plays a critical role as the master passes information on to the initiate. This form of Halstedian training has served as the basis for the apprenticeship-style learning throughout the ages (9, 41). Anatomic relationships are vividly demonstrated along with the consequences for each action. Unfortunately, the patient can be an unforgiving teacher. There are real-time pressures during the procedure, and patient interests must come first. Safety and efficacy cannot be sacrificed for educational purposes (25).



ONLINE
DIGITAL
VIDEO

Ventriculostomy is a high volume, low morbidity procedure that is diagnostic and potentially lifesaving. There is a real risk of hemorrhage (1–6%) and infection (2–12%) associated with catheter placement (17, 23). Optimal catheter trajectory and positioning are critical to prevent damage to vital neural and vascular structures (7, 10, 29, 31, 34).

Ventriculostomy is likely the first neurosurgical procedure that a young neurosurgery resident will learn and use on a regular basis. Although faculty or senior residents may proctor early cases, the high volume of the procedure means that most residents must become proficient very early in their training. In an ideal world, the resident would understand the proper techniques and "feel" of the procedure before performing it on a live patient (30).

We have designed a haptics-based, three-dimensional (3-D) platform for ventriculostomy placement. The simulator recreates the surface landmarks that guide catheter trajectory as well as the tactile feedback as the catheter passes through the brain parenchyma and into the ventricle. This technology may potentially be used to train residents how to perform a ventriculostomy, allowing them to become proficient before even laying hands on a patient. The ventriculostomy simulator module also serves as a proof-of-concept to assess the feasibility of designing a more realistic neurosurgical virtual/augmented reality platform that can be used for a variety of part-task procedural simulations.

MATERIALS AND METHODS

(see video at web site)

We used the ImmersiveTouch (ImmersiveTouch, Inc., Chicago, IL) virtual reality platform developed at the University of Illinois, Chicago (27, 28). This system can be described as an augmented virtual reality system (26). This platform combines real-time haptic feedback with high resolution stereoscopic display. An electromagnetic head-tracking protocol provides for realistic and changing perspective as the user moves his or her head. A translucent (half-silvered) mirror is used to create an augmented reality environment that integrates the surgeon's hands, the virtual catheter, and the virtual patient's head in a common working volume.

The graphics and haptics collocation achieved by the ImmersiveTouch platform is critical to the realistic recreation of the surgical experience. The user sees his or her own hand holding a virtual catheter in the same location and space as they would for the actual procedure; there is no shift in anatomic perspective as with endoscopy or previous computer-based simulations. The user can interact with the virtual objects using both hands; the surgeon holds the haptic stylus (Sensable Technologies, Woburn, MA) in one hand and defines arbitrary 3-D cutting planes with the other hand while holding a SpaceGrips (LaserAid, Los Gatos, CA) interface.

The ImmersiveTouch software uses a series of software modules to acquire, process, and render the graphic and haptic data. These are then seamlessly integrated on the hardware platform (*Fig. 1*). Each stage of the data processing is briefly described below.

Volume Data Preprocessing

Magnetic resonance or computed tomographic Dicom data sets are gathered from our clinical patient population and are stripped of all identifying personal data. These are segmented and combined to create a 3-D virtual volume of the patient's head. The three-dimensional, polygonal isosurfaces corresponding to the skin, bone, brain, and ventricles are extracted from the 3-D volume and exported to the rendering module.

Head and Hand Tracking

An electromagnetic sensor (Ascension Technology Corp., Burlington, VT) attached to the stereoscopic goggles (Real D Scientific, Beverly Hills, CA) tracks head movements to compute the viewer's perspective while the user moves his or her head around the virtual patient's head to locate the landmarks. Another sensor located inside the SpaceGrips tracks the surgeon's hand to define a cut-away plane and the light source to better display the virtual head volume and its virtual contents.

Haptics Rendering

The system reads the position and orientation of the haptic stylus, computes the collision detections between the virtual catheter and the imported 3-D isosurfaces, and generates the corresponding force feedback. Each isosurface is assigned different haptic characteristics, according to certain parameters: stiffness, viscosity, static friction and dynamic friction. Therefore, the surgeon can feel the different surfaces and textures of the skin, bone, and brain. A viscosity effect is felt as the catheter passes through the gelatinous parenchyma of the brain. As soon as the catheter breaks the dense ependymal ventricular lining, the viscosity effect ceases, providing the surgeon with the distinct "popping" sensation.

Graphics Rendering

The virtual environment is organized with a virtual patient head displayed using the imported 3-D isosurfaces and lighting with a special perspective camera node. The camera node allows for display of stereoscopic perspective to each of the surgeon's eyes according to the position and head orientation. An infrared emitter coordinates the 3-D goggles' shutters for each eye with the stereoscopic, frame-sequential display. A cut-away tool on the SpaceGrip device allows for visualization of deeper surfaces and volumes. The graphics are displayed using a high-resolution cathode ray tube monitor and transreflective mirror. The ImmersiveTouch system offers high display resolution (1600 × 1200 pixels) and high visual acuity (20/24.74), which is important to clearly see the depth markings of the virtual catheter and small details of the head anatomy.

RESULTS

The user sits at the working table space of the ImmersiveTouch simulator (*Fig. 2*). The electromagnetically-tracked, stereoscopic goggles are worn to view the reflected virtual reality image on the partially-mirrored viewing surface. A shift in the user's head causes a corresponding change in perspective around the virtual patient's head. These changes also collocate with the user's hands as viewed through the transreflective (mirrored) viewing surface. The virtual catheter and assorted virtual working tools (light source, cut-away instruments) also project into the collocational space.

The user is presented with a virtual patient head, viewed from an anterorostral perspective, similar to patient positioning for ventriculostomy placement in the operating room or intensive care unit. The head is supine and raised about 30 degrees,

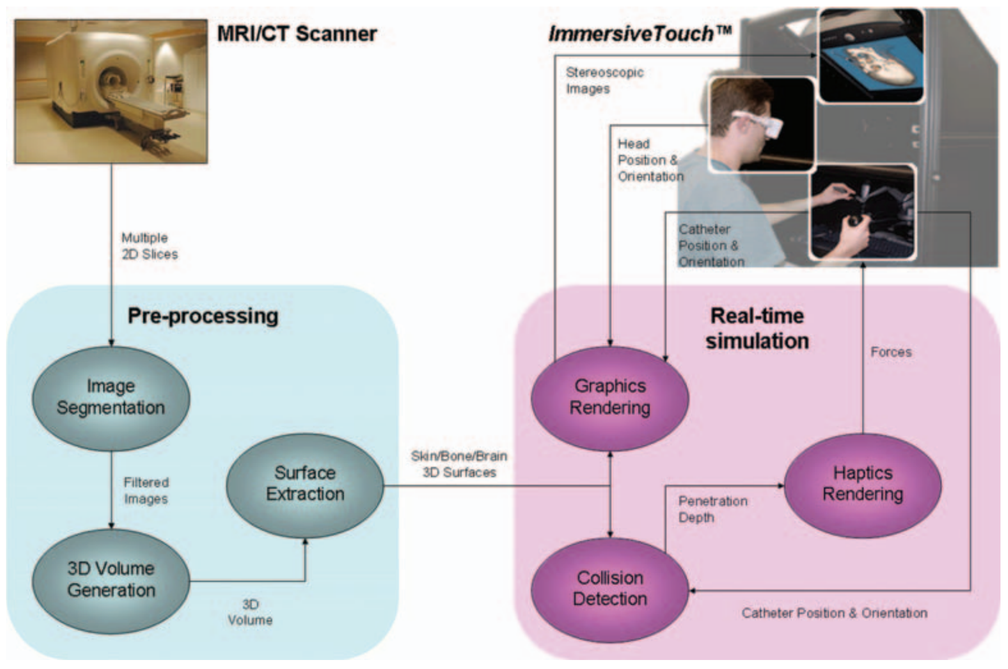


FIGURE 1. *Actual anatomic data from computed tomographic or magnetic resonance imaging Dicom images are processed to create the virtual 3-D polygonal isosurfaces. The data are extracted into anatomic layers (e.g., skin, skull, brain, ventricle) to recreate the surface volumes. This information is further processed for graphics rendering and display (e.g., lighting, perspective) as well as collision detection for haptics modeling. All of these computations are integrated within the ImmersiveTouch platform for procedural simulation.*

but minor adjustments are permitted by the user. Superficial landmarks such as the ipsilateral medial canthus and tragus are easily visualized by changing the user's perspective (i.e., looking around the head) just as with the actual procedure.

We use a "part-task" modular paradigm for this simulation. This assumes that only critical components of the procedure must be modeled and simulated. As such, hair clipping, prepping and draping, skin incision, and calvarial trephination are presumed before the procedure. A preexisting scalp incision and burr hole over Kocher's point on the right are provided on the virtual head.

By grasping the haptic stylus, the user is able to see a virtual catheter with appropriate measurement demarcations. This catheter is collocated in the user's hand so that the perception is that one is actually holding a catheter. Note, this is not a simulation of a virtual hand and catheter, but is rather superimposition of the virtual tool onto the live hand *(Fig. 3)*.

The catheter tip is positioned over the burr hole at Kocher's point while optimal trajectory is determined. A variety of techniques may be used to assure ventricular cannulation, but we teach our residents to aim the catheter toward the ipsilateral medial canthus and tragus. In general, with such a trajectory, the catheter will generally be perpendicular to the plane tangential to the skull at the entry point (36).

For our preliminary simulations, we used computed tomographic scan data sets from patients with overt hydrocephalus to simplify the early modeling of the ventricular system. Future renditions will include normal and slit ventricles as well as deep structures shifted in response to masses (e.g., tumors, hematomas). Naturally, the user would have to take these factors into account and modify the initial trajectory appropriately.

As the catheter is advanced past the calvarium and enters the modeled brain, the user feels a distinct increase in resistance. Not only can the viscosity of the brain parenchyma be simulated, but the interface at the junction between the layered volumes can also be separately modeled to recreate the sensation of the catheter piercing the pia or ependyma. When the catheter reaches the appropriate volumetric depth, there is a sudden release in haptic resistance corresponding to the "pop" often experienced when the ventricle is cannulated. The ruler on the ventricular catheter may also be used to gauge the expected depth to ventricular cannulation.

When the user thinks he or she has successfully placed the ventricular catheter, the SpaceGrip controller in the left hand is used to freeze the virtual catheter in position. If the virtual catheter is in the virtual ventricular system, it will turn green; otherwise its color will be red. The user may then use the cutaway tool and rotate the head to visualize the exact location of the catheter tip and correlate the experience with technique (*Fig. 4*). The procedure may be restarted in an iterative process to reinforce proper technique.

The haptic characteristics and graphic rendering for the simulator was modified based on feedback from neurosurgical faculty and senior residents. The final product was universally felt to simulate the tactile and visual components of the actual procedure.

DISCUSSION

Given the current pressures impacting neurosurgical education, the development of virtual reality simulators offers the possibility of improving both the educational process and patient safety. This applies not only to the training of novice neurosurgeons, but also those maintaining or recertifying their surgical skill set (8). The time-honored techniques for surgical education, including textbook and atlas descriptions, com-

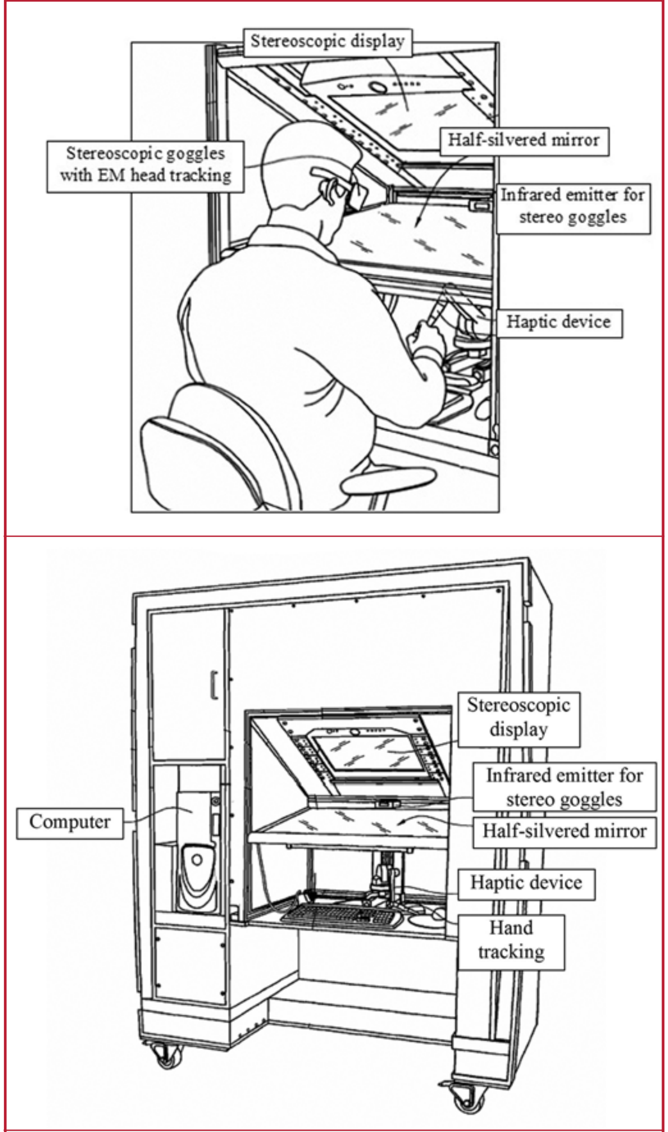


FIGURE 2. *The ImmersiveTouch virtual reality platform consists of a cathode ray tube monitor mounted above and projecting onto a transreflective mirror. The space below the mirror contains the haptic feedback stylus and SpaceGrips tool. The virtual reality space perfectly overlaps the user's workspace to create an augmented reality. The stereoscopic goggles are actively tracked with light-emitting diodes to adjust viewer perspective in response to user head movement.*

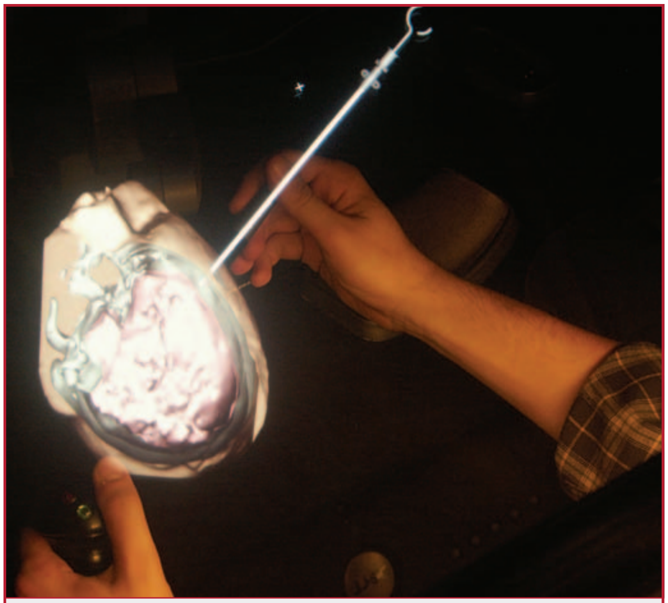


FIGURE 3. *Collocation of the virtual volumes (virtual patient head and catheter) with real-space (e.g., the user's hands) is critical to the platform's realistic virtual reality. This effect is maintained even as the view perspective dynamically shifts around the working volume. The simulation is accomplished through use of electromagnetically-tracked stereoscopic goggles and the transreflective (mirrored) viewing surface.*

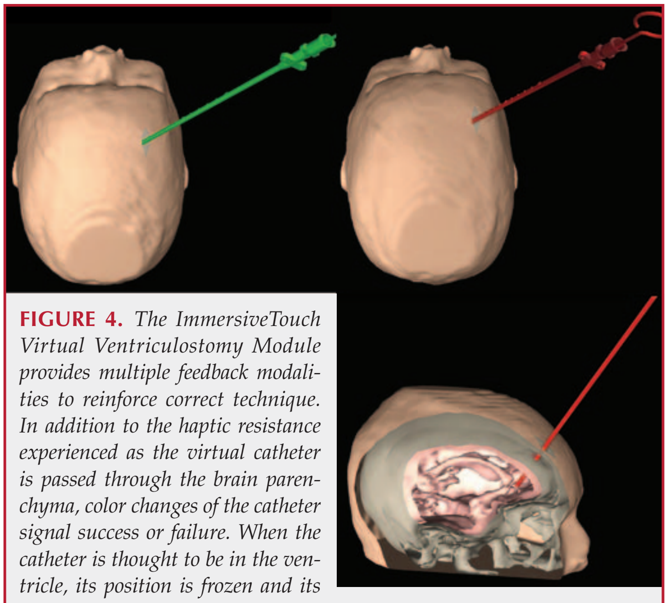


FIGURE 4. *The ImmersiveTouch Virtual Ventriculostomy Module provides multiple feedback modalities to reinforce correct technique. In addition to the haptic resistance experienced as the virtual catheter is passed through the brain parenchyma, color changes of the catheter signal success or failure. When the catheter is thought to be in the ventricle, its position is frozen and its color will change to green if the ventricle was cannulated; if not, the catheter will be colored red. Additionally, the cut-away tool can be used to directly visualize the ventricular system and the catheter's relationship to it.*

puter-rendering, and cadaveric dissection, often fall short of the goal of imparting the full procedural knowledge and psychomotor skills. Ideally, the student should be able to acquire the anatomic knowledge and psychomotor skill set and "jump-start" the learning process before performing a procedure on a live patient (20).

Neurosurgical procedures, particularly cranial applications, lend themselves to virtual reality simulation. The working space around the cranium is limited. Anatomic relationships within the cranium are generally fixed, and respiratory or somatic movements do not significantly impair imaging and rendering. The same issues that make cranial procedures so suitable for intraoperative navigation also apply to virtual operative simulation. The eloquence of so many cerebral structures also allows little room for error, making the need for skill set acquisition before the procedure that much more significant. The emergence of realistic neurosurgical simulators has been predicted since the mid-1990s when the explosion in computer processing speed seemed to presage future developments (3).

A great variety of neurosurgical simulators have been described, many of which have focused on enhanced visualization through stereoscopic 3-D rendering to better demonstrate complex anatomic relationships (5, 14, 32). Haptic feedback algorithms provide yet another sensory cue to further enhance realism. These simulation components have been used for a variety of surgical simulators with application for laparoscopic, endoscopic, and microsurgical training (1, 5, 6, 11, 22, 37, 39). Often, these simulations can import patient-specific data and act as a form of "operative rehearsal" (4, 19, 38, 41). One of the most exciting avenues of exploration has been the use of virtual reality simulators to model not only force resistance, but also neurological tissue deformations in response to force perturbations (13, 21, 44). Although these issues are not currently incorporated into our virtual reality platform, they present exciting avenues of exploration for future part-task modules.

Ventriculostomy simulation has been attempted previously using computer-based platforms. In 2000, John and Phillips (15) and Philips and John (35) developed a cross-platform, web-based ventriculostomy simulator. This early simulator allowed virtual catheter positioning and trajectory determination relative to a 3-D virtual head. An auditory cue in lieu of tactile feedback signaled ventricular cannulation. Catheter manipulation with the mouse was rudimentary and no tactile feedback was provided. This form of visually reinforced learning for ventriculostomy training has also been described using operative neuronavigational platforms (22). The effectiveness of these simulators is limited to improving the understanding of anatomic relationships relative to catheter position and trajectory.

The first generation of haptic ventriculostomy simulators provided tactile feedback using a haptic stylus device during virtual ventricular cannulation (10, 24). The user manipulated the virtual catheter with the haptic device stylus in a virtual reality-haptic environment implemented for the Reachin display (Reachin Technologies AB, Stockholm, Sweden). Although this development created considerable excitement as a novelty device for ventricular cannulation, its usefulness for teaching and measuring neurosurgical expertise was still very limited. More recent efforts using haptic-driven ventriculostomy simulators have attempted to correlate simulator training with increased procedural efficacy. Despite graphical "near-to-reality" characteristics, these systems still require "suspension of disbelief" by the user (43).

Another recent attempt at ventriculostomy simulation has been published by Panchaphongsaphak et al. (33). These authors use the BrainTrain simulator (Sensory Motor Systems Laboratory, Zurich, Switzerland) and a one-degree-of-freedom haptic stylus to simulate the advancement of a catheter into a physical brain model. The virtual rendering allows for virtual trajectory visualization and force feedback. Because the platform uses a physical model brain, dynamic graphical rendering is not required. The authors found errors in haptic feedback up to 20% from those expected; it is also not clear whether or not the device could simulate the anticipated ependymal "pop" as the ventricle is canulated.

During an actual ventriculostomy, the surgeon orients the catheter and defines a trajectory based on superficial landmarks. The surgeon must move his or her head from one side of the patient's head to the other to locate the landmarks in the axial and sagittal planes. Head tracking is critical to simulate a dynamic viewing perspective. Previous models have provided only static virtual heads that are cumbersome to manipulate and rotate. These fall short of simulating the psychomotor skill set involved in selecting catheter trajectory.

Another important feature of realistic simulation is perfect overlap the 3-D virtual catheter image with the haptic stylus. This effectively collocates the two so the user feels as though he or she is holding the catheter. This collocated perspective takes into account the user's head position through head tracking. Previous attempts at ventriculostomy simulation were not able to address this issue, and the attention of the surgeon was diverted from the simulated procedure toward overcoming the visual dissociation of real and virtual objects.

The combination of stereoscopic 3-D display with dynamic perspective tracking, haptic feedback, and collocation of real and virtual object volumes allows our virtual reality ventriculostomy simulation to overcome many earlier limitations. For the development of the ImmersiveTouch platform, we drew upon previous experience at our institution. The Personal Augmented Reality Immersive System, also developed at the University of Illinois, represents the earliest virtual/augmented reality platform to effectively combine haptic feedback with dynamic graphical rendering in a computer-based simulator (2, 16, 40). The user's hands are collocated within the virtual reality working space and changes in head position alter graphical 3-D perspective. The platform has been used to model cranial implants in a virtual 3-D environment. The system is limited by lower visual acuity (20/112), which would not provide adequate visualization of finer detail (e.g., catheter depth markings) for our ventriculostomy model.

Current limitations of our ventriculostomy simulator include its inability to detect and register force feedback for sidewall collisions. For instance, the module cannot produce force resistance from the burr hole walls if the catheter is laterally translocated. The haptic stylus also cannot reproduce torque, which, although not critical for a ventriculostomy simulation, would be indispensable for procedures such as screw placement or trephination. Although the haptic stylus allows six degrees of freedom, the physical size of its working arm and the constraints of the augmented reality working space beneath the transreflective mirror do limit the user's range of motion.

The part-task paradigm used for this module also presumes that certain steps of the procedure (e.g., scalp incision) do not need to be simulated. This can be partially remedied by combining individual modules to recreate complete procedures.

Still, by omitting intervening, non-critical segments, the overall realism is diminished.

The cost for the platform's highly specialized hardware components can be in excess of tens of thousands of dollars, and these are often extremely use-specific to the range of motions being replicated. The very particular needs of a software module are also labor intensive. Nonetheless, the ImmersiveTouch platform should be robust enough to accommodate a variety of surgical modules, and with broader applications than to just ventriculostomy simulation, the "cost-per-module" should decrease dramatically.

Although the ventriculostomy module was originally conceived as a "proof-of-concept," future developments will include permutations to the original data set to recreate slit or shifted ventricles for the purpose of increasing complexity. Our goal is to continue with the development of procedural "modules," each simulating a single technical component (e.g., burr hole trephination). Several modules can then be assembled to reproduce an entire procedure using a "part-task" simulation paradigm. Broader application to additional neurosurgical procedures such as craniotomy and pedicle screw placement is planned.

CONCLUSION

We have developed a realistic haptics-based, augmented, virtual reality simulator for neurosurgical education. The ImmersiveTouch platform creates a virtual reality environment using stereoscopic, dynamic 3-D graphics rendering, haptic feedback, and virtual/real-world object collocation. To assess the feasibility and realism of the virtual/augmented reality platform, we designed a ventriculostomy placement module. The simulator accurately reproduces the part-task experience of cannulating the ventricle with a virtual ventricular catheter. More complex modular simulations including cranial approaches and spinal instrumentation will exploit the full potential of the platform. Given the importance of neurosugical simulation for training and recertification, this simulator represents an important step forward.

Disclosure

The ImmersiveTouch platform and the novel ventriculostomy application have been disclosed to the University of Illinois. The authors (ML, PPB, FTC) have interest in the business development of this product.

REFERENCES

1. Agus M, Giachetti A, Gobbetti E, Zanetti G, Zorcolo A, John NW, Stone RJ: Mastoidectomy simulation with combined visual and haptic feedback. **Stud Health Technol Inform** 85:17–23, 2002.
2. Ai Z, Evenhouse R, Leigh J, Charbel F, Rasmussen M: New tools for sculpting cranial implants in a shared haptic augmented reality environment. **Stud Health Technol Inform** 119:7–12, 2005.
3. Apuzzo ML: New dimensions of neurosurgery in the realm of high technology: Possibilities, practicalities, realities. **Neurosurgery** 38:625–639, 1996.
4. Auer LM, Auer DP: Virtual endoscopy for planning and simulation of minimally invasive neurosurgery. **Neurosurgery** 43:529–548, 1998.
5. Bernardo A, Preul MC, Zabramski JM, Spetzler RF: A three-dimensional interactive virtual dissection model to simulate transpetrous surgical avenues. **Neurosurgery** 52:499–505, 2003.
6. Brown N, Natsupakpong S, Johannsen S, Manjila S, Cai Q, Liberatore V, Cohen AR, Cavusoglu MC: Virtual environment-based training simulator for endoscopic third ventriculostomy. **Stud Health Technol Inform** 119:73–75, 2005.
7. Bullock R, Chestnut RM, Clifton G, Ghajar J, Marion DW, Narayan RK, Newell DW, Pitts LH, Rosner MJ, Wilberger JW: Guidelines for the management of severe head injury. Brain Trauma Foundation. **Eur J Emerg Med** 3:109–127, 1996.
8. Burchiel K: Virtual reality. **J Neurosurg** 100:583–584, 2004.
9. Chinnock C: Virtual reality in surgery and medicine. **Hosp Technol Ser** 13:1–48, 1994.
10. Cros O, Volden M, Flaaris JJ, Brix L, Pedersen CF, Hansen KV, Larsen OV, Østergaard LR, Haase J: Simulating the puncture of the human ventricle. Presented at the 10th Annual Medicine Meets Virtual Reality Conference, Newport Beach, January 23–26, 2002.
11. Cusimano MD: Virtual reality surgery: Neurosurgery and the contemporary landscape a three-dimensional interactive virtual dissection model to simulate transpetrous surgical avenues. **Neurosurgery** 53:1010–1012, 2003.
12. *Deleted in proof.*
13. Hansen KV, Brix L, Pedersen CF, Haase JP, Larsen OV: Modelling of interaction between a spatula and a human brain. **Med Image Anal** 8:23–33, 2004.
14. Henn JS, Lemole GM Jr, Ferreira MA, Gonzalez LF, Schornak M, Preul MC, Spetzler RF: Interactive stereoscopic virtual reality: A new tool for neurosurgical education. **J Neurosurg** 96:144–149, 2002.
15. John NW, Phillips N: Surgical simulators using the WWW. **Stud Health Technol Inform** 70:146–152, 2000.
16. Johnson A, Sandin D, Dawe G, Qiu Z, Thongrong S, Plepys D: Developing the PARIS: Using the CAVE to Prototype a New VR Display, in *Proceedings of IPT 2000: Immersive Projection Technology Workshop*, Ames, June 19–20, 2000 (CD-ROM).
17. Kanter MJ, Narayan RK: Management of head injury. Intracranial pressure monitoring. **Neurosurg Clin N Am** 2:257–265, 1991.
18. Kikinis R, Gleason PL, Moriarty TM, Moore MR, Alexander E 3rd, Steig PE, Matsumae M, Lorensen WE, Cline HE, Black PM, Jolesz FA: Computer-assisted interactive three-dimensional planning for neurosurgical procedures. **Neurosurgery** 38:640–651, 1996.
19. Kockro RA, Serra S, Tseng-Tsai Y, Chan C, Yih-Yian S, Gim-Guan C, Lee E, Hoe LY, Hern N, Nowinski WL: Planning and simulation of neurosurgery in a virtual reality environment. **Neurosurgery** 46:118–137, 2000.
20. Korndorffer JR Jr, Dunne JB, Sierra R, Stefanidis D, Touchard CL, Scott DJ: Simulator training for laparoscopic suturing using performance goals translates to the operating room. **J Am Coll Surg** 201:23–29, 2005.
21. Koyama T, Hongo K, Tanaka Y, Kobayashi S: Simulation of the surgical manipulation involved in clipping a basilar artery aneurysm: Concepts of virtual clipping. **J Neurosurg** 93:355–360, 2000.
22. Krombach G, Ganser A, Fricke C, Rohde V, Reinges M, Gilsbach J, Spetzger U: Virtual placement of frontal ventricular catheters using frameless neuronavigation: An "unbloody training" for young neurosurgeons. **Minim Invasive Neurosurg** 43:171–175, 2000.
23. Lang EW, Chestnut RM: Intracranial pressure. Monitoring and management. **Neurosurg Clin N Am** 5:573–605, 1994.
24. Larsen OV, Haase J, Østergaard LR, Hansen KV, Nielsen H: The Virtual Brain Project—Development of a neurosurgical simulator. **Stud Health Technol Inform** 81:256–262, 2001.
25. Leach DC: Simulation: It's about respect. **ACGME Bulletin** December:2–3, 2005.
26. Liu CY, Spicer M, Apuzzo ML: The genesis of neurosurgery and the evolution of the neurosurgical operative environment: Part II—Concepts for future development, 2003 and beyond. **Neurosurgery** 52:20–35, 2003.
27. Luciano C, Banerjee P, Florea L, Dawe G: Design of the ImmersiveTouch: A high-performance haptic augmented VR system. Proceedings of the 11th International Conference on Human-Computer Interaction, Las Vegas, NV, 2005.
28. Luciano C, Banerjee P, Lemole GM Jr, Charbel F: Second generation haptic ventriculostomy simulator using the ImmersiveTouch system. **Stud Health Technol Inform** 119:343–348, 2006.

29. Narayan RK, Kishore PR, Becker DP, Ward JD, Enas GG, Greenberg RP, Domingues Da Silva A, Lipper MH, Choi SC, Mayhall CG, Lutz HA 3rd, Young HF: Intracranial pressure: To monitor or not to monitor? A review of our experience with severe head injury. **J Neurosurg** 56:650–659, 1982.
30. Oh M: Learning by (not really) doing: Surgical simulators for education and fun. **AANS Bull** 15:36, 2006.
31. O'Leary ST, Kole MK, Hoover DA, Hysell SE, Thomas A, Shaffrey CI: Efficacy of the Ghajar Guide revisited: A prospective study. **J Neurosurg** 92:801–803, 2000.
32. Panchaphongsaphak B, Burgkart R, Riener R: BrainTrain: Brain simulator for medical VR application. **Stud Health Technol Inform** 111:378–384, 2005.
33. Panchaphongsaphak B, Stutzer D, Schwyter E, Bernays RL, Reiner R: Haptic device for a ventricular shunt insertion simulator. **Stud Health Technol Inform** 119:428–430, 2006.
34. Paramore CG, Turner DA: Relative risks of ventriculostomy infection and morbidity. **Acta Neurochir (Wien)** 127:79–84, 1994.
35. Phillips NI, John NW: Web-based surgical simulation for ventricular catheterization. **Neurosurgery** 46:933–937, 2000.
36. Prabhu SS, Zauner A, Bullock MR: Surgical management of traumatic brain injury, in Winn HR, Dacey RG Jr (eds): *Youmans Neurological Surgery*. Philadelphia, WB Saunders, 2004, ed 5, pp. 5145–5180.
37. Riegel T, Alberti O, Retsch R, Shiratori V, Hellwig D, Bertalanffy H: Relationship of virtual reality neuroendoscopic simulations to actual imaging. **Minim Invasive Neurosurg** 43:176–180, 2000.
38. Rohde V, Krombach GA, Struffert T, Gilsbach JM: Virtual MRI endoscopy: Detection of anomolies of the ventricular anatomy and its possible role as a presurgical planning tool for endoscopic third ventriculostomy. **Acta Neurochir (Wein)** 143:1085–1091, 2001.
39. Rowe RA: Virtual reality surgical simulation for neurosurgical training paper #760. **Neurosurgery** 39:652, 1996 (abstr).
40. Scharver C, Evenhouse R, Johnson A, Leigh J: Designing Cranial Implants in a Haptic Augmented Reality Environment. **Communications of the ACM** 27:32–38, 2004.
41. Spicer MA, Apuzzo ML: Virtual reality surgery: Neurosurgery and the contemporary landscape. **Neurosurgery** 52:489–497, 2003.
42. Spicer MA, van Velsen M, Caffrey JP, Apuzzo ML: Virtual reality neurosurgery: A simulator blueprint. **Neurosurgery** 54:783–798, 2004.
43. Strauss G, Trantakis C, Nowatius E, Falk V, Maass H, Cakmak K, Strauss E, Dietz A, Meixensberger J, Bootz F, Kuhnapfel U: Virtual training in head- and neurosurgery [in German]. **Laryngorhinootologie** 84:335–344, 2005.
44. Wang P, Becker AA, Jones IA, Glover AT, Benford SD, Greenhalgh CM, Vloeberghs M: A virtual reality surgery simulation of cutting and retraction in neurosurgery with force-feedback. **Comput Methods Programs Biomed** 84:11–18, 2006.

Acknowledgments

This work has been funded in part by NSF Grant DNI 9988136, and NIST-ATP Cooperative Agreement 70NANB1H3014. The participation of the University of Illinois, Chicago neurosurgery residents and rotating medical students is greatly appreciated.

COMMENTS

Lemole et al. have designed a computer-based simulation of ventricular drain placement, which combines both dynamic and visual feedback. Given, as the authors note, the low morbidity of ventriculostomy placement and the frequency with which it is performed, we do not believe there is a need for a virtual reality simulator to train neurosurgical residents in this procedure. However, the article does serve as a "proof of concept" that haptic and visual feedback may be combined in a neurosurgical virtual reality simulator. We look forward to the continued evolution of virtual reality and its application to neurosurgical education.

Francisco Ponce
Robert F. Spetzler
Phoenix, Arizona

Lemole et al. have presented a new and unique adjunct to neurosurgical education. Their second generation surgical simulation technology is well suited for ventriculostomy placement education. This is one of the first steps toward a more global haptic and dynamic surgical simulation feedback paradigm. It is difficult to conceive of the simulation of a complex cranial or spine surgery procedure for education purposes. On the other hand, who would have thought 20 years ago that we would be treating the majority of aneurysms via endovascular techniques today?

Edward C. Benzel
Cleveland, Ohio

The authors describe an augmented reality simulation of lateral ventriculostomy technique that includes virtual object space and tactile feedback through haptic modeling. The authors, who have a vested financial interest in the technology described, hope that it will become a component of a modular system to educate neurosurgical residents. Since my first attempt at this more than a decade ago, computer power has improved exponentially, making this hope one that is increasingly achievable. The authors are to be commended for this important step forward, particularly with the haptic feedback, which is a critical component of surgical simulation.

The developed system is clearly very costly to develop but the hope is that, once developed, unit costs will decline. For this to occur in neurosurgery, a significant number of units or a large price per unit will need to be sold to recoup the development costs. Thus, systems with the ability to be used as modules across a variety of settings have the best chance to meet this need. This advance will provide one of those steps toward this goal.

Application of the principle of educational validity to the current situation demands that we demonstrate that the knowledge, skills, and attitudes learned in the simulation are transferable to real-world settings such as the operating room. Although it is difficult, properly designed educational experiments can begin to accomplish this task. To show that the system can actually improve the rate and extent of learning over traditional methods, with less cost to the student, teachers, and patients, requires a concerted long-term effort. We hope to see some of this from these and other authors in the future. To be able to use such a system for credentialing or recertification requires an intensive battery of evaluations aimed not only at reproducibility, validity, and human factor interactions but also to important considerations such as a standard setting (1).

Technologies like the one demonstrated here will have a definite role in the future of neurosurgical education; however, the development and maintenance of an astute and effective clinician requires much more than the assembly of a series of technical skills. A risk of such technology is that, as teachers, we think that the simulator can do everything; thus, we abandon our duty to the full needs of the student and, ultimately, to our patients. Teachers will need to know how to effectively integrate such tools into the development of the future neurosurgeon.

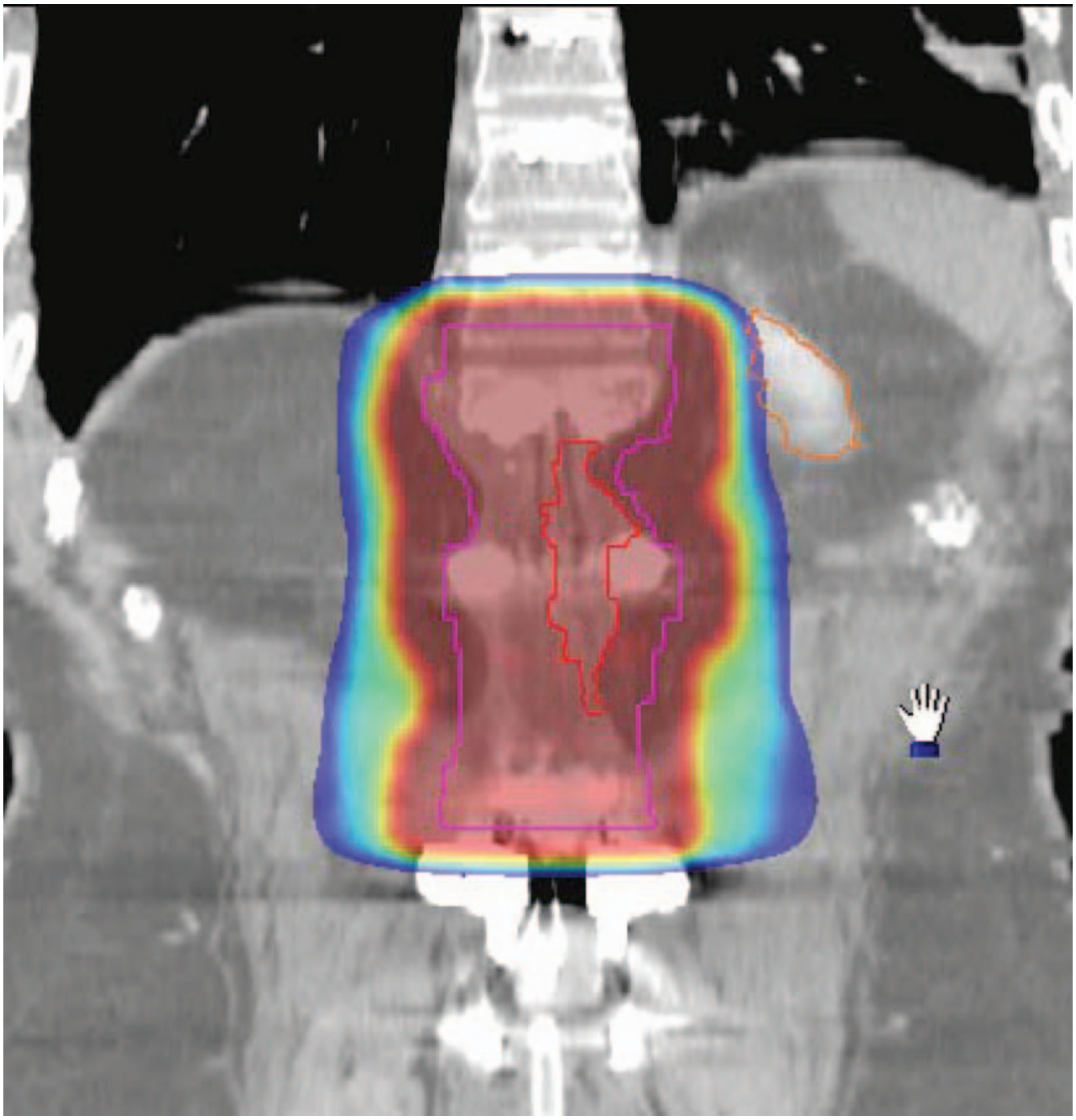
Michael D. Cusimano
Toronto, Canada

---

1. Cusimano MD: Standard setting in medical education. **Acad Med** 71 [Suppl 10]:S112–S120, 1996.

The authors are to be congratulated on developing an excellent and appealing simulation model. This is just the tip of the iceberg in resident education. The new reality in resident hours will mean that getting up to speed will require those who are dedicated to the education of residents to compact and innovate the requisite lessons in psychomotor skills. The authors and their engineering colleagues at the University of Illinois did just that. They wisely chose a procedure that is high volume and essential to master and designed a simulation model that uses both visual and haptic feedback. Before showing up in the operating room, the resident can now practice using this computer-generated system with the hope of improving his/her confidence and psychomotor skills. The result will be improved patient safety and, hopefully, improved technical skills in a shorter period of time. Like all computer software and hardware, the computer-generated simulation will only improve over time, and the procedures covered will become more sophisticated and complex. Time will tell whether or not this approach combined with other novel approaches in resident education can help us train more effectively in a shorter period of time.

Richard G. Ellenbogen
Seattle, Washington



Proton beam therapy. Dose planning for proton beam treatment of a lumbar spine chordoma. Courtesy of Northeast Proton Therapy Center, Massachusetts General Hospital, Harvard Medical School.