Virtual Frontiers, Part 2: Role of Virtual Reality Technology in Neurosurgery

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ABSTRACT During the last decade, advances in biomedical imaging and computation have enabled more precise and accurate determination of tissue structure and function, along with three-dimensional (3-D) reconstruction, visualization, and intuitive manipulation of such multimodality data. The practice of neurosurgery has benefited from such advances, as reflected by their facilitation of surgical diagnosis and planning, miniaturization of operative corridors, and enhancement of intraoperative localization and effectiveness at the target site. Hand in hand with these developments has been the incorporation of a variety of new technologies, both physical and virtual, into the surgical "environment," with the overriding aim of optimizing surgical performance. For neurosurgery, the accurate 3-D reconstruction and intuitive, interactive, and immersive display of patient-specific multimodality imaging data in real-time represents the ultimate goal of virtual reality (VR) technology. Computer graphics, stereotaxis, electrophysiological monitoring, and robotics will augment both the surgeon's direct visualization of a patient, either local or remote, and ability to carry out an operation in the safest and most efficacious manner. However, practical issues such as cost versus benefit, the need for appropriate training and an interdisciplinary approach, and error detection must be evaluated as this technology evolves. The present work aims to detail the contributions of VR technology in neurosurgery and address the contemporary issues and future directions associated with its development and implementation.

Keywords Virtual reality, 3-D reconstruction, neurosurgery

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TECHNICAL AND CONCEPTUAL CHALLENGES IN NEUROSURGERY

Several major technical and conceptual challenges exist in contemporary neurosurgery. These include: determination of the precise focus of pathology and its relationship to surrounding (normal) vital structures; estimating the 3-D extent of lesions and, at times, obtaining precise measurements; planning the best site of craniotomy and safest route of navigation; and knowing the exact location of the surgeon's instruments in the brain.[1-8] Specific challenges associated with particular neurosurgical operations or procedures are listed in Table 1.

Computer-assisted Neurosurgery

Computer-assisted surgery planning methods have been applied in neurosurgery for over a decade, primarily through the use of stereotactic systems for intraoperative 3-D localization and navigation. These systems require accurate segmentation (i.e., tissue differentiation) and visualization of multimodality image data of the head, including external soft tissue, skull, brain tissues, CSF, eyes, paranasal sinuses, and musculature.[9] Often, external reference frames and fiducial markers or internally applied fiducials must also be imaged and localized within the context of the 3-D anatomic volume image.[8,9] The added resources of preoperative structural and functional information derived from multimodality 3-D imaging and intraoperative navigational and localization information derived from stereotaxy represent major advancements in the practice of neurosurgery. The "minimal access craniotomy" (in keeping with

Table 1 Technical and Conceptual Challenges According to Neurosurgical Procedure

Cerebrovascular: Access to deep-seated lesions; precise location, extent and relationship of feeding, nidus, and draining vessels; extent of carotid atheroma; "goodness of fit" of stents
Craniofacial Reconstruction: Complex operative plan; "goodness of fit" of autologous or prosthetic grafts
Epilepsy: Precise seizure focus and accuracy of co-registration of target with preoperative anatomical and functional studies
Tumor: Orientation within brain tissue; proximity to eloquent areas; safe margins of resection
Neuroendoscopy: Visibility, tissue manipulation, orientation, and navigation
Radiosurgery: Maximal lesion irradiation while sparing surrounding normal structures
Skull Base: Limited peripheral visibility within and around lesion; precise tumor-bone and tumor-vessel/nerve relationships

the concept of minimally invasive neurosurgery), with its advantages of reducing tissue disruption, neurologic and wound complications, operative time, and patient discomfort compared with traditional techniques,[1,5,10] is undoubtedly a by-product of these advances. However, a major remaining constraint is that real-time, *intra*operative high-resolution imaging with 3-D interactive display is not currently available.

Meeting These Challenges

The solution to the aforementioned problem perhaps lies in five spheres of research and development (Fig. 1): the use of high-performance computational systems; the use of intraoperative high-resolution imaging; the implementation of new and appropriate operating room (OR) designs; the adequate training of surgeons in VR technology; and the physical implementation of this technology in the OR itself.

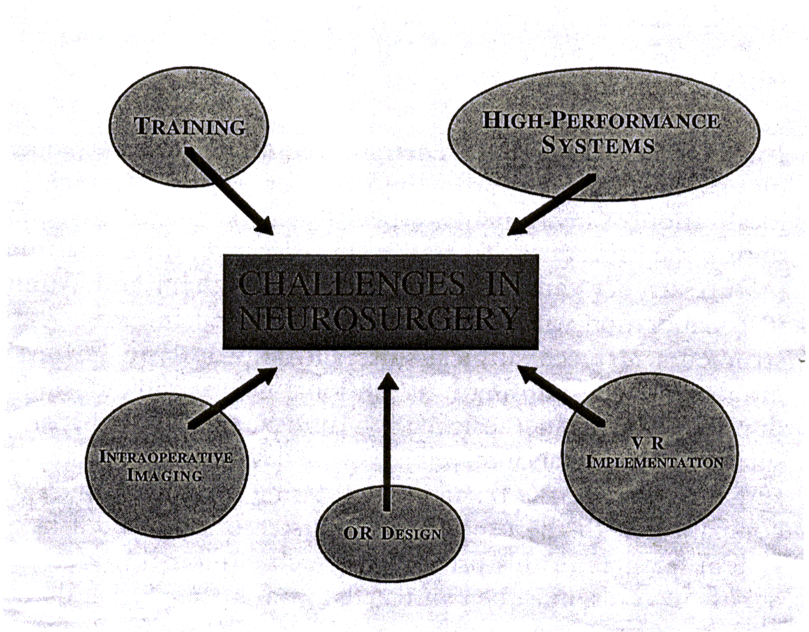

Fig. 1 Contemporary technical and conceptual challenges in neurosurgery can be effectively addressed by the development of high-performance computational systems, intraoperative high-resolution imaging, and the design of operating rooms (OR) accommodating new VR and scanning devices, in addition to adequate training of surgeons in VR techniques, and the adoption and implementation of this evolving technology in neurosurgical practice.

High-performance Systems. There is a great need for high-performance hardware and powerful software that can enable a surgeon to interact with multimodality images in an intuitive manner (i.e., in volumes and three dimensions).[11] At the Mayo Clinic, a software package known as ANALYZE™ has been developed specifically with this necessity in mind.[9] This software features integrated tools for fully interactive display, manipulation, and measurement of multidimensional image data. Importantly, the software is intuitive and user-friendly, and runs efficiently on many standard workstations without the need for special-purpose hardware.[9] It has been used productively at many institutions by physicians, surgeons, and scientists on images obtained from magnetic resonance imaging (MRI), X-ray computed tomography (CT), positron emission tomography (PET), single photon emission computed tomography (SPECT), and ultrasound scanning, as well as from conventional light, electron, and confocal microscopy.[9] The greatly enhanced level of information about the surgical environment provided by this technology has the potential of enabling surgeons to perform more complete and safe procedures.[7,9,12] Examples of neurosurgical (or related) procedures carried out at our institution with the aid of this technology include complex cerebrovascular cases, epilepsy surgery, brain tumor resection, and craniofacial reconstruction.[7,9] The utility of ANALYZE™ is demonstrated in Figures 2 through 5.

Intraoperative Imaging. There is a requirement for intraoperative high-resolution imaging to address the need for precise and real-time intracranial localization of instruments, especially in the face of tissue positional shifts during the procedure. To realize this objective, the Departments of Surgery (Neurosurgery) and Radiology of the Brigham and Women's Hospital, in collaboration with General Electric Medical Imaging Systems, have constructed a research surgical suite with a prototype *open* MRI scanner for intraoperative use during interventional neuroradiologic and surgical procedures.[12,13] The scanner features two large parallel torus-shaped magnets placed side by side with an intervening space between the tori to allow the neurosurgeon access to the operative site during imaging. Although the scanner is compatible with the use of frameless stereotaxy (a built-in optical tracking system features in this prototype), such equipment, and all operating and anesthetic tools, must be constructed from materials that do not generate significant artifacts and are safe to use in an MRI environment.[12,13]

OR Design. The neurosurgical OR must be designed in a manner that can effectively accommodate these expanding imaging and visualization technologies. A prototype OR fulfilling this requirement has been built at the University of Southern California, Los Angeles.[14] Referred to as "Visualization System One," the OR designers have placed considerable emphasis on achieving a more spacious environment, with a key goal being the maximization of visualization, from the incorporation of surgical rehearsal and planning systems to the enhanced use and display of intraoperative imaging modalities, in addition to accommodation of advanced microscope and stereotaxy systems, robotic assistants, and on-line text and atlas libraries.[2,14] The addition of a research and imaging laboratory in close proximity to the main operating suite facilitates the close interaction required between the surgeon, engineer, and audiovisual technician.[14]

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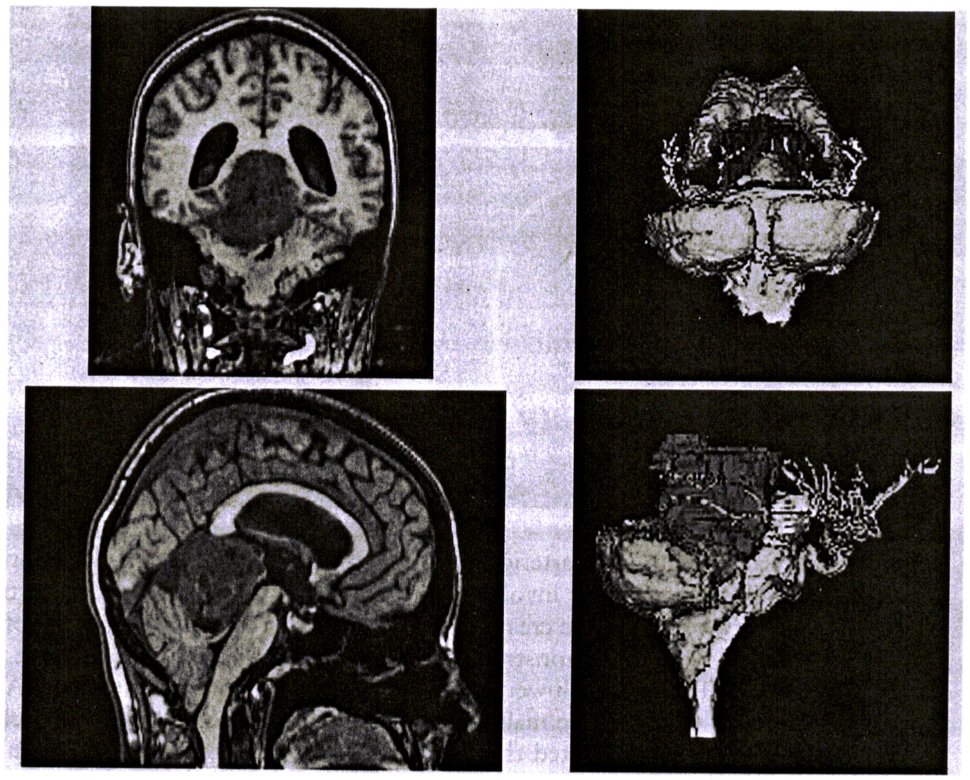

Fig. 2 Patient with pilocytic astrocytoma. As part of surgical planning, VR visualization methods were used to examine the patient-specific anatomy in 3-D to determine the full spatial extent of the lesion and its proximity to vital structures. Coronal and sagittal T1-weighted MR images are shown in the left panels, with corresponding volume rendered views of the segmented (i.e., differentiated) image data on the right. The 3-D images depict the extent of the tumor, its proximity to the cerebellum and brainstem, and its associated blood vessels. The clinical usefulness of volume rendering is considerably enhanced by user interactivity and the addition of color.

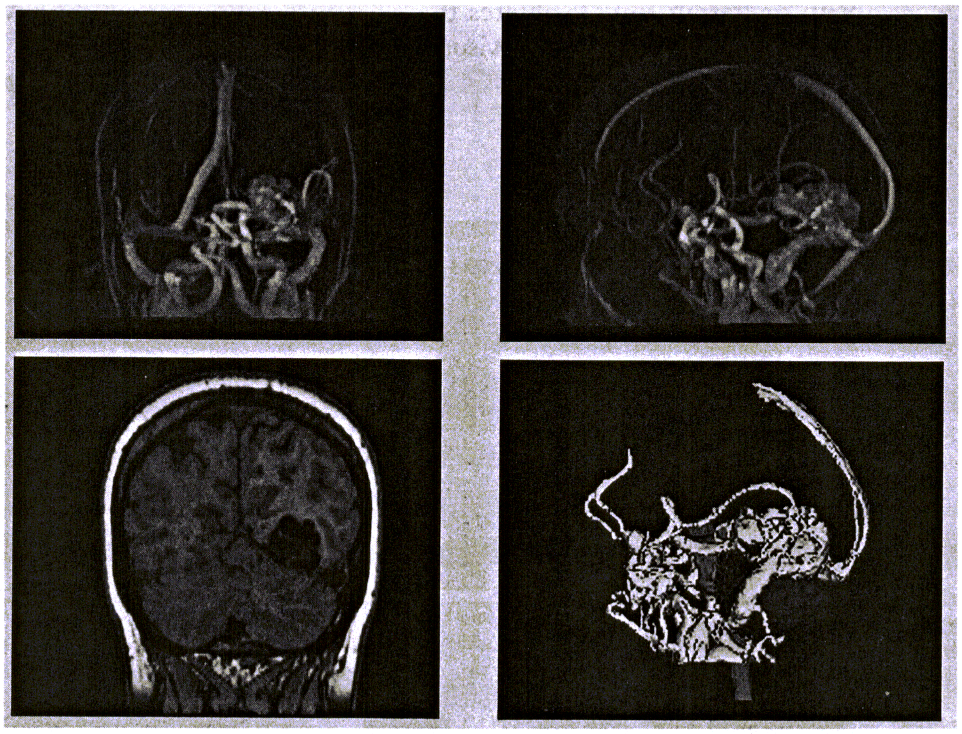

Fig. 3 Patient with large arteriovenous malformation (AVM). The lesion was examined in 3-D to identify the involved cerebral vessels and proximity to vital structures. The upper two panels were created using a maximum intensity projection of the MR angiography data to demonstrate the vasculature. The lower left image is a T1-weighted MRI, while the lower right image is a volume rendering of the AVM vessels. The true extent of the malformation and its relationship to the cerebellum and brainstem is best appreciated through interactive visualization and manipulation of the data (further enhanced by the use of color).

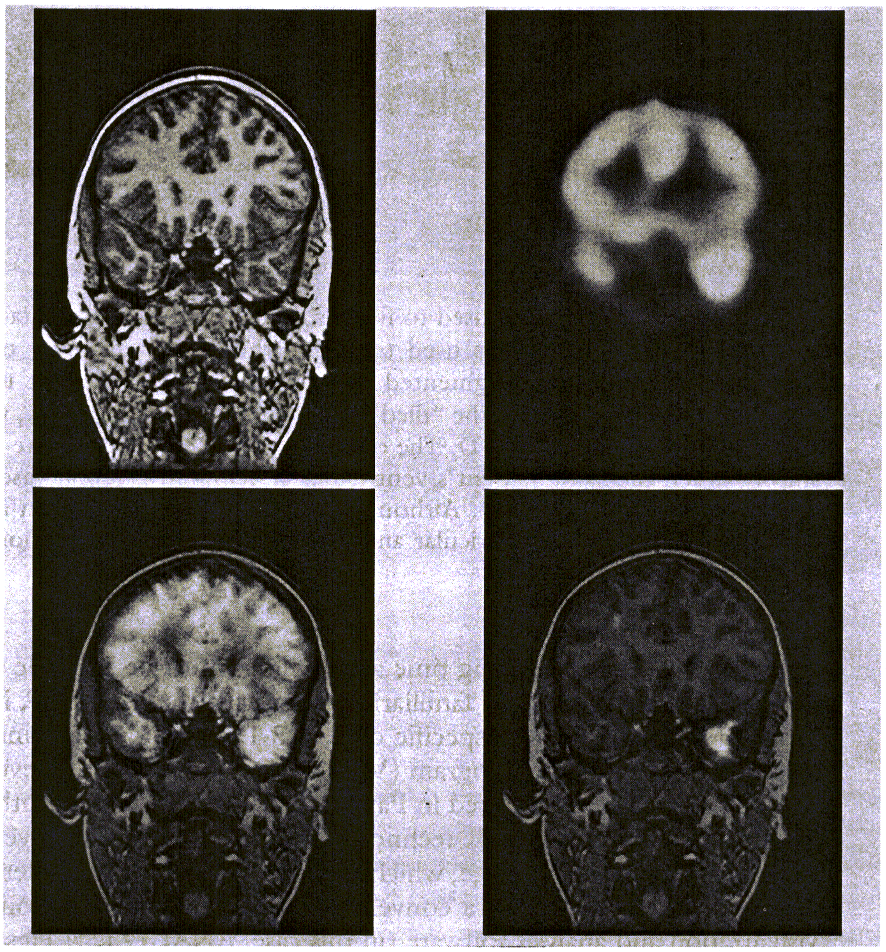

Fig. 4 Patient with temporal lobe epilepsy. Image processing methods are involved in surgical planning for epilepsy.[47] An MRI was acquired (upper left panel), in addition to ictal (upper right panel) and interictal (not shown) SPECT scans of the patient. The SPECT scans were registered to the MRI data (lower left) and, using digital subtraction methods, the precise location of the seizure focus in the left temporal lobe was determined (lower right panel).

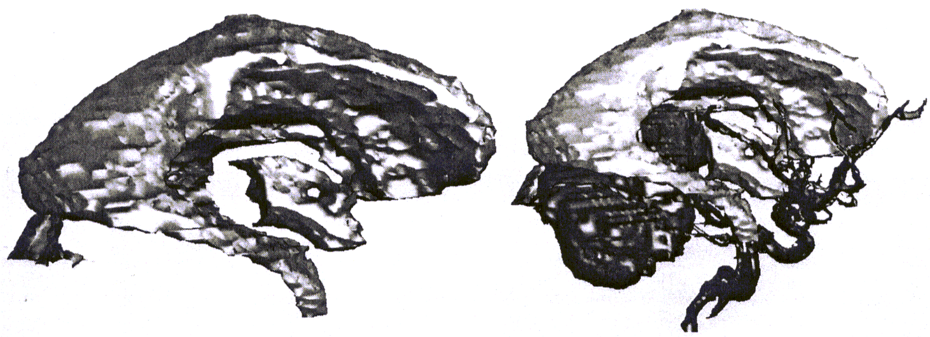

Fig. 5 VR methods may be used to further examine preoperative data in real time. A process known as tiling is used to define the surface anatomy of individual "objects" that have been segmented (i.e., differentiated) from the total volume image data. The left object is the "tiled" ventricular system of a patient, which can be viewed and manipulated in 3-D. The objects on the right demonstrate the relationship between the same patient's ventricular system and cerebral vasculature and a large pilocytic astrocytoma. Although not shown here, tiling can also be used to demonstrate the intraventricular anatomy (the basis of the "fly-though" images created in virtual endoscopy).

Training. Adequate training time and facilities must be available to surgeons utilizing VR technology to familiarize them with the use of VR interfaces in the exploration of patient-specific data in 3-D. With this in mind, a Virtual Reality Assisted Surgery Program (VRASP) is currently under development at the Mayo Clinic. As described in Part 1, VRASP represents a synthesis of 3-D biomedical imaging and VR technology aimed at facilitating overall surgical performance.[15] The first stage, which has been successfully completed, involves planning the procedure at a conventional computer workstation using 3-D visualization and analysis software (in this case, ANALYZE™; Figs. 2 through 5). The second stage, which is currently being evaluated by several of our physicians and surgeons, involves rehearsal of the operation using a high-performance computer, VR input/output (I/O) devices (such as head-mounted displays and datagloves), and patient-specific 3-D volume scan data. It should be emphasized that the creation of critical events in this virtual environment does not risk human life and allows for the planning and repetition of the task that is to be performed or learned.[16,17] A similar approach has been used in the development of virtual endoscopy[15–21] and virtual anesthesia training.[22–25] The third stage of VRASP, which remains to be developed, involves incorporation of this system into the OR itself, accurately and instantaneously fusing the preoperative scanning, planning, and rehearsal 3-D image data with the real image of the patient being operated.[15]

Implementation. Perhaps the most important solution to the technical and conceptual challenges of neurosurgery lies in the physical implementation of new sensory and robotic interfaces, both local and remote, that achieve dynamic, fully immersive, multisensory fusion of real and virtual data streams.[15,16,26] Although this technology is still under development, as described above and detailed in the previous chapter great progress has been made in the establishment of a working infrastructure.

CONTEMPORARY ISSUES

In almost any field, the major activities of a profession consist of learning, design, analysis, action, and communication.[27] Although VR may benefit all these activities and improve the quality of the end product or its impact, several broad issues must be addressed with regard to its overall benefit (Table 2).

Cost

There is an immense economic burden involved in technological advancement and application, a factor relevant not only in the United States, but also globally.[2] Undoubtedly, the ongoing changes in the structure and function of the health system in this country will affect the ability of many institutions to pursue or acquire the technology described. As summarized by Apuzzo,[2] Health Maintenance Organizations (HMOs), which champion medical care by pursuit of the "cheapest bidder," facilitate economic confinement of effort and diversion of revenue from the health care economy and, in attempting to drive costs down, undermine critical investment in the technological and academic progress of the medical system. Undoubtedly, there is virtue in regulating the acquisition of the more expensive stereotactic and VR-based systems until adequate cost-benefit analyses have been carried out.[1] On the one hand, it is reasonable to expect that improved surgical planning, rehearsal, and performance facilitated by this technology will result in an overall reduction of operative time, patient complications, and length of hospitalization,

Table 2 Issues Relating to Development and Implementation of VR Technology

Overall benefit	Fidelity of simulations
Cost	Ergonomics
User training	Equipment and personnel in OR
Image processing time	Hygiene during prolonged immersion
Usage time	Error recognition and handling
Interdisciplinary approach	Ongoing need for objective evaluation

while allowing more efficient use of the surgeon's time and hospital OR facilities, thereby resulting in an overall reduction of costs. On the other hand, this must be weighed against the cost of purchase and maintenance of equipment and the technique's impact on the history of the disease itself.[28] Workstations and high-performance graphic computers such as those from Silicon Graphics are needed, with sophisticated parts and specialist labor imposing budgets that may run into hundreds of thousands of dollars.[16] Simpler and cheaper medical VR systems have been constructed using personal computers with 3-D graphics accelerators; however, the slower frame-rates and more limited overall capabilities are major constraining issues in this setting.[29]

Time and Training

There is little doubt that more time will need to be devoted by the surgeon to familiarization with the technology and its accurate, safe, and effective usage. Lengthy image processing and procedure rehearsal times may also be a factor, especially in the setting of virtual endoscopy.[19] All neurosurgery residents of the future will need to become proficient in minimally invasive operative techniques (which are associated with reduced operation time and patient morbidity), and increasingly will require training in the use of computer-assisted visualization and navigation systems.[1,10] It is intended that the use of VR systems to simulate surgical scenarios will augment operative training and allow evaluation of technical competence prior to use in patients.[1]

Practicalities

The use of advanced imaging and VR systems mandates an interdisciplinary approach between the medical/surgical team, the radiology team, and the technical support team.[11,30] The technology that is developed and used in the setting of surgery must provide real-time interaction and high-resolution, realistic graphics, regardless of where the image is projected or whether the image is a simulation or a fusion of real and synthetic data. The comfort and practicality of the devices developed must also be considered, along with regulation of the amount of imaging and VR equipment in the OR and the number of personnel involved in its implementation in that setting. Finally, personal hygiene during prolonged immersion involving shared user devices such as head-mounted displays and datagloves must also be taken into consideration.[27]

Errors and Patient Safety

The need to maintain the highest level of patient safety mandates adequate training in the use of advanced technologies and the recognition of errors and common pitfalls.[1,30,31] In the setting of stereotaxy, errors may arise from alteration in the patient's head position after initial registration, line-of-sight obstruction between emitters and detectors, imaging techniques that facilitate geometric distortions and other artifacts, erroneous point selection and vector calculation, poor mechanical couplings, human operator error, and tissue displacement or brain-shift.[30–34] Knowledge of the overall reliability of the system is essential to the surgeon and can be gleaned by closely analyzing the error quantities of each component of the system from the beginning to the end of the neurosurgical and imaging procedures.[33] In the setting of robotic assistants, the issue of patient safety must also be comprehensively addressed.[1] This can be accomplished by setting the highest standards for the robot's mechanical, electrical, and software components, utilization of robot-monitoring subsystems, and the incorporation of devices that freeze robot motion or interrupt power supply to the robot as part of error recovery strategies.[4]

THE FUTURE

Pertaining to the fields of medicine and surgery, the rapid evolution of computers, imaging techniques, and communications technology, coupled with the ongoing search for the safest course and most efficacious outcome in patient care, mandates our active interest and involvement in the growth of revolutionary technologies such as VR. The following represent some important developments in this field.

Teleoperations

Several organizations have begun to address the issue of teleoperations (remote conferencing, consultations, clinicoradiologic databases, and/or operation), especially in the fields of medicine and surgery.[27,35–37] In addition to the requirement for appropriate and sophisticated communication hardware (e.g., reliable satellite links, optic cables, and audiovisual hardware) and VR tools (such as the various multisensorial I/O devices), adequate operator training must also be achieved.[27,38,39] Telepresence surgery (remote surgery) has been the interest of NASA (space surgery performed from earth), the military (battlefield surgery or surgical assistance rendered from remote locations), and medical organizations (providing adequate health care in underserved or underdeveloped regions).[27,36] The surgeon "operates" locally on a virtual patient model (with multisensory cues), while his or her actions are transmitted via high-speed networks or satellite to a robotic assistant operating on a real but distant patient.[27] Feedback to the surgeon is derived from the robot's visual (camera), tactile (arm), and auditory (microphone) sensors, while the patient's vital biodata is coded and transmitted by the remote anesthetist or technician.[27] The robot's surgical view, rapidly transmitted to the surgeon's head-mounted display, is overlaid on the virtual body, thus providing guidance for the surgeon. Although such a system may seem futuristic, prototype systems have been developed and described.[27,39,40] Interestingly, such human-computer interfaces allow scalability, whereby a gross movement by the surgeon may be translated to a microsurgical maneuver by the teleoperator.[39]

Robotics

Several groups have explored the integration of robotic technology into the neurosurgical OR.[41–44] Here, the development of robotic instrumentation specifically designed for operative tasks has been demonstrated to be feasible, safe, and efficient, especially in stereotaxy. Recent developments include microscope support systems that employ a ceiling-mounted robotic microscope holder that efficiently combines the functionalities of stereotactic guidance and instrument micromanipulation.[31,45] There is considerable speculation as to the applicability of robotic control technologies and the employment of VR computer interfaces to integrate the various imaging databases obtained for a given patient.[31] The development of artificial intelligence programs may permit the evolution of intuitive behavior by the robot, such as safe and efficacious autonavigation through the brain.[1,46] Many stereotactic neurosurgical cases have now been performed successfully using robots.[1,41–45]

Teaching

Development of the "virtual cadaver" is just around the corner.[9] The National Library of Medicine (NLM) has advanced the concept of the virtual patient with the Visible Human Project, which aimed to create a digital database of a complete human male and female cadaver in MRI, CT and cryogenic modes.[16] VR systems of the near future will feature sensory input and feedback (including visual, auditory, olfactory, and tactile), as well as realistic, dynamic, and fully interactive 3-D displays. Educational systems using high-resolution 3-D imaging and VR, augmented with natural language user query and system response functions, will constitute powerful and important uses of these techniques in the twenty-first century.[9] In this context, a VR surgical simulator has been described[38,40] that involves a separate operative site (composed of a surgical manipulator, paired video cameras, and a stereophonic microphone) and surgical workstation (composed of a 3-D monitor, handcontrollers, and stereophonic speakers) coupled in real-time. Further, many software companies are producing libraries of 3-D modeled "objects."[16] In the near future, it is likely that libraries of realistic medical apparatus, organs, and tissues will be available for use "off the shelf"; all the clinician has to do is specify the environment and the objects with which he or she would like to work.[16]

CONCLUSIONS

The field of neurosurgery has benefited greatly from recent advances in imaging and computer technology that have facilitated operative planning and performance. The incorporation of VR technology into contemporary neurosurgical practice affords the additional advantage of highly intuitive and interactive, real-time display of patient-specific multimodality data throughout the entire perioperative period, thus effectively addressing its various technical and conceptual challenges. In a clinical setting, VR technology will not only impact favorably on operative planning, rehearsal, and performance, but will also enhance surgical training and medical teaching, practice, and research as a whole. There is, however, an ongoing need to evaluate major issues associated with the development and implementation of new VR-based systems and techniques, including cost-benefit analysis, demands on time and training, and the detection and management of device and system errors. It is feasible to expect that the future practice of neurosurgery will evolve with, and be greatly augmented by, this highly important technology.

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REFERENCES

1. Rosenfeld JV. Minimally invasive neurosurgery. Aust NZ J Surg 1996;66:553–559
2. Apuzzo MLJ. New dimensions in neurosurgery in the realm of high technology: possibilities, practicalities, realities. Neurosurgery 1996;38:625–639
3. Kikinis R, Gleason PL, Moriarty TM, et al. Computer-assisted interactive three-dimensional planning for neurosurgical procedures. Neurosurgery 1996;38:640–651
4. Sawaya R, Rambo WM Jr, Hammoud MA, Ligon BL. Advances in surgery for brain tumors. Neurol Clin 1995;13:757–771
5. Barnett GH, Kormos DW, Steiner CP, Weisenberger J. Use of a frameless, armless stereotactic wand for brain tumor localization with two-dimensional and three-dimensional neuroimaging. Neurosurgery 1993;33:674–678
6. Nakajima S, Atsumi H, Bhalerao AH, et al. Computer-assisted surgical planning for cerebrovascular surgery. Neurosurgery 1997;41:403–410
7. Meyer FB, Grady RE, Abel MD, et al. Resection of a large temporooccipital parenchymal arteriovenous fistula by using deep hypothermic circulatory bypass: case report. J Neurosurg 1997;87:934–939
8. Roberts DW. Fundamentals of registration. In: Barnett GH, Roberts DW, Maciunas RJ (eds). Image-Guided Neurosurgery: Clinical Applications of Surgical Navigation. St. Louis: Quality Medical Publishing; 1998:3–15
9. Robb RA. Three Dimensional Biomedical Imaging: Principles and Practice. New York: VCH Publishers; 1995:1–287

10. Barnett GH. Minimal access craniotomy. In: Barnett GH, Roberts DW, Maciunas RJ (eds). Image-Guided Neurosurgery: Clinical Applications of Surgical Navigation. St. Louis: Quality Medical Publishing; 1998:63–71
11. Wiet GJ, Stredney DL, Yagel R, Sessanna DJ. Using advanced simulation technology for cranial base tumor evaluation. Otolaryngol Clin North Am 1998;31:341–356
12. Alexander E III, Kikinis R, Black PM, Jolesz FA. Intraoperative magnetic resonance imaging. In: Barnett GH, Roberts DW, Maciunas RJ (eds). Image-Guided Neurosurgery: Clinical Applications of Surgical Navigation. St. Louis: Quality Medical Publishing; 1998:215–227
13. Black PM, Moriarty TM, Alexander E III, et al. Development and implementation of intraoperative magnetic resonance imaging and its neurosurgical applications. Neurosurgery 1997;41:831–845
14. Apuzzo MLJ, Weinberg RA. Architecture and functional design of advanced neurosurgical operating environments. Neurosurgery 1993;33:663–673
15. Robb RA. Surgery in the year 2000: planning and performing with virtual reality. BioJapan '96 Symposium Proc; 1996:81–92
16. Ahmed M, Meech JF, Timoney A. Virtual reality in medicine. Br J Urol 1997;80 (suppl 3): 46–52
17. Satava RM, Robb RA. Virtual endoscopy: application of 3D visualization to medical diagnosis. Presence 1997;6:179–197
18. Soferman Z, Blythe D, John NW. Advanced graphics behind medical virtual reality: evolution of algorithms, hardware, and software interfaces. Proc IEEE 1998;86:531–554
19. Rubin GD, Beaulieu CF, Argiro V, et al. Perspective volume rendering of CT and MR images: applications for endoscopic imaging. Radiology 1996;199:321–330
20. Rosenberg LB. Human interface hardware for virtual laparoscopic surgery. In: Morgan K, Satava RM, Sieburg HB, Mattheus R, Christensen JP (eds).Interactive Technology and the New Paradigm for Healthcare. Amsterdam: IOS Press and Ohmsha; 1995:322–325
21. Satava RM, Jones SB. Virtual reality. In: Satava RM (ed). Cybersurgery: Advanced Technologies for Surgical Practice. New York: Wiley-Liss; 1998:75–96
22. Hoffman H, Vu D. Virtual reality: teaching tool of the twenty-first century? Acad Med 1997;72:1076–1081
23. Raibert M, Playter R, Krummel TM. The use of virtual reality haptic device in surgical training. Acad Med 1998;73:596–597
24. Trelease RB. The virtual anatomy practical: a stereoscopic 3D interactive multimedia computer examination program. Clin Anat 1998;11:89–94
25. Blezek DJ, Robb RA, Camp JJ, Nauss LA, Martin DP. Simulation of spinal nerve blocks for training anesthesiology residents. SPIE 1998;3262:45–51
26. Camp JJ, Cameron BM, Blezek D, Robb RA. Virtual reality in medicine and biology. FGCS 1998;14:91–108
27. Burdea G, Coiffet P. Virtual Reality Technology. New York: John Wiley & Sons; 1994:1–370
28. Bingaman WE, Barnett GH. Social and economic impact of surgical navigation systems. In: Barnett GH, Roberts DW, Maciunas RJ (eds). Image-Guided Neurosurgery: Clinical Applications of Surgical Navigation. St. Louis: Quality Medical Publishing; 1998:231–249
29. Hovden T, Lillesveen R, Forfang SK, Halaas A. Building a virtual invasive patient on a budget. In: Westwood JD, Hoffman HM, Stredney D, Weghorst SJ (eds). Medicine Meets Virtual Reality. Amsterdam: IOS Press and Ohmsha; 1998:373–374
30. Maciunas RJ. Pitfalls. In: Barnett GH, Roberts DW, Maciunas RJ (eds). Image-Guided Neurosurgery: Clinical Applications of Surgical Navigation. St. Louis: Quality Medical Publishing; 1998:43–60

31. Barnett GH, Steiner CP, Roberts DW. Surgical navigation system technologies. In: Barnett GH, Roberts DW, Maciunas RJ (eds). Image-Guided Neurosurgery: Clinical Applications of Surgical Navigation. St. Louis: Quality Medical Publishing; 1998:17–32.
32. Walton L, Hampshire A, Forster DMC, Kemeny AA. A phantom study to assess the accuracy of stereotactic localization, using T1-weighted magnetic resonance imaging with the Leksell stereotactic system. Neurosurgery 1996;38:170–178
33. Kaus M, Steinmeier R, Sporer T, Ganslandt O, Fahlsbusch R. Technical accuracy of a neuronavigation system with a high–precision mechanical micromanipulator. Neurosurgery 1997;41:1431–1427
34. Maciunas RJ, Galloway RL, Latimer JW. The application accuracy of stereotactic frames. Neurosurgery 1994;35:682–695
35. Marsh A, Simistira F, Robb R. VR in medicine: virtual colonoscopy. FGCS 1998;551:1–12
36. Balch DC. Telemedicine in rural North Carolina. In: Morgan K, Satava RM, Sieburg HB, Mattheus R, Christensen JP (eds). Interactive Technology and the New Paradigm for Healthcare. Amsterdam: IOS Press and Ohmsha; 1995:15–20
37. Kotelly G, Wilson A. Computing systems use object-oriented software. Vision Systems Design 1998(January issue):26–30
38. Satava RM, Ellis SR. Human interface technology: an essential tool for the modern surgeon. Surg Endosc 1994;8:817–820
39. Simon IB. Surgery 2001: concepts of telepresence surgery. Surg Endosc 1993;7:462–463
40. Satava RM. Virtual reality surgical simulator: the first steps. Surg Endosc 1993;7:203–205
41. Kwoh YS, Hou J, Jonckheere EA, Hayati S. A robot with improved absolute positioning accuracy for stereotactic brain surgery. IEEE Trans Biomed Eng 1988;35:153–160
42. Drake JM, Joy M, Goldenberg A, Kreindler D. Computer- and robot-assisted resection of thalamic astrocytomas in children. Neurosurgery 1991;29:27–31
43. Benabid AL, Lavallée S, Hoffman D, Cinquin P, Demongeot J, Danel F. Computer-driven robot for stereotactic neurosurgery. In: Kelly PJ, Kall BA (eds). Computers in Stereotactic Neurosurgery. Boston: Blackwell; 1992:330–342
44. Fankhauser H, Glauser D, Flury P, et al. Robot for CT-guided stereotactic neurosurgery. Stereotact Funct Neurosurg 1994;63:93–98
45. Giorgi C, Eisenberg H, Costi G, Gallo E, Garibotto G, Casolino DS. Robot-assisted microscope for neurosurgery. J Image Guided Surg 1995;1:158–163
46. Benabid AL. A routine stereotactic procedure in 2003. Neurosurgery 1993;33:660–662
47. O'Brien TJ, So EL, Mullan BP, et al. Subtraction ictal SPECT co-registered to MRI improves clinical usefulness of SPECT in localizing the surgical seizure focus. Neurology 1998;50:445–454