Computer-assisted Neurosurgery

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Beginning in the latter half of the 20th century, the field of neurological surgery has been transformed by a technological revolution providing increasingly capable and affordable digital computer technology. This process has affected how we select patients to undergo surgery, how that surgery is performed, and how we assess the success of our therapy. Conversely, it influences how patients choose their physician, how we are compensated for our work, and how others evaluate us as surgeons. Because information technology impacts so many aspects of our professional lives, it is instructive to analyze circumstances in which the benefits of computer technology have been incorporated consciously into clinical practice to the benefit of our patients. By harnessing computers to assist us in surgery, we have added a new tool to our armamentarium that affords us new opportunities to promote healing.

To begin this analysis, it is helpful to consider what forces drive the incorporation of new technology into surgery. Clearly, economic considerations play a fundamental role. When a newer technology allows us to perform a neurosurgical operation at a lesser expense, especially if it does not necessitate overwhelming transitional costs, this provides a clear motivation to move to this new technology. Conversely, when an older technology becomes more expensive to use, then alternative methods are reassessed. Apart from immediate economic advantage, a new technology may bring with it new capabilities to the surgeon. These may make current operations easier, more effective, or safer. New surgeries may become possible as well. In a marketplace of surgical practitioners, these capabilities would confer a competitive advantage to the practitioner who successfully incorporates them into practice in a timely fashion. In addition to rational motivations, new technology attracts early adopters by its "desirability." This may be considered a promise, as yet unfulfilled, of some future benefits.

The physician-driven incorporation of computer technology into our clinical practice is mirrored by the behavior of our patients, who also increasingly use computer assistance in navigating their clinical encounters. With ready access to the Internet through sophisticated search engines, patients routinely search disease-related websites, physician and healthcare institutional websites, and services such as Leapfrog that assess, rate, and rank both physicians and hospitals. Increasingly, patients seek to engage physicians in Email consultations, perioperative questions, and follow-up instructions. Disease- or device-related Internet chat rooms have proliferated, imparting various degrees of patient experience and medical opinion.

In this context, the term "Computer Assisted Surgery" should be understood to include:

- Digital patient data
- Image guidance
- Real-time intraoperative feedback
- Robotics
- Neural prostheses
- Outcomes analysis

DIGITAL PATIENT DATA

It can be safely said of all contemporary neurosurgical practitioners that we increasingly use computers to assist us in our preoperative evaluations of our patients. The transformation of medical imaging through digital tomographic techniques has affected every aspect of our clinical care. We have been able to amplify our accuracy and precision of diagnosis, while doing so in a significantly safer and less invasive manner. Digital summation of electrical impulse has provided us with improved electrophysiological techniques for diagnosis and ongoing monitoring of our patients' central and peripheral nervous system electrical activity. The documentation of our clinical encounters with patients is in the process of becoming digitally secured through electronic medical records programs. When a question arises in the practitioner's mind about a disease or therapy, Internet-enabled medical literature review provides a means of access to an extensive reference library.

IMAGE GUIDANCE

Perhaps the single most potent application of computer technology to neurosurgical practice has been that of image guidance of surgical interventions. Image guidance has been widely integrated into the practice of cranial surgery and has

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also been demonstrated to have specific utility in selected spinal surgeries.

To use digital imaging databases as maps for surgical navigation, it is necessary to register, or map, them onto the physical space of the patient's anatomy. In a similar fashion, one image volume is registered to another image volume, so that both may be used simultaneously. Various techniques have been used for this, including atlases, intrinsic anatomic points of reference as well as extrinsic fiducial markers, curve and surface matching, mutual information/intensity-based matching of images, moment and principal axis analysis of images, correlation and interactive methods, and, most recently, initial efforts employing non-rigid registration, sometimes labeled as "warping" or "morphing."

To effect the registration of image data onto the physical space of the patient's anatomy, a physical device is used to identify shared points, surface, or regions. Often, although not always, this same device can then be used as an intraoperative pointer to display the relevant image data associated with a given anatomic point, or to guide a probe to a position pre-selected in imaging space. Termed an "interactive localization device," this instrument may or may not be physically linked to the patient's anatomy. Linked interactive localization devices include stereotactic frames with their localization devices and their mechanical aiming arcs, passive articulated localization arms, active articulated robotic arms, or intraoperative magnetic resonance imaging or computed tomographic scanners. Non-linked interactive localization devices include those that use sonic triangulation, active infrared emitting diode optical triangulation, passive optical projection imaging, passive reflective optical localization, x-ray projection imaging, electromagnetic field deflection with radiofrequency transmission, gyroscopes, gravitometers, inertial guidance mechanisms, and two- or three-dimensional ultrasound methods.

Having accomplished registration, image guidance systems must successfully display image information to the surgeon in an intuitive, interactive, and useful way. The computer software and data display allow the surgeon access to capabilities that may include treatment planning, application-specific software, the use of multiple images, reformatting of images, the rendering of pseudo three-dimensional displays of data, multiple user-selected two- or three-dimensional display formats, virtual reality and augmented reality interfaces, telepresence and telesurgical applications, haptic interfaces, and modules for training and self-assessment.

The reformatting of computer-generated tomographic image data volumes entails the reslicing of the data cube at an oblique angle to that used during image acquisition, in order to display the imaging data in a manner more relevant to the surgical line of perspective employed during the course of surgery. The canonical forms of reformatted images are termed axial, coronal, sagittal, and oblique slices. Rendering is a process whereby the imaging data is edited to display a defined and selected surface as a pseudo-three-dimensional picture more conducive to intuitive appreciation of anatomic relationships.

Augmented reality displays of patient imaging data have been used to advantage in "heads-up" displays projected through an ocular of an operating microscope onto the retina of the operating surgeon. When the microscope line of sight is tracked by an image guidance system and used as an interactive localization device, this makes possible the enrichment of information available to the surgeon. This "overlay" of images has been limited by the technical challenges of parallax, magnification, resolution, intensity, and perspective inherent to integrating analog images from the microscope optics with digital images rendered from the tomographic data sets. Special headsets and goggles have also been used in experimental systems of augmented reality displays, with similar limitations and challenges. As digital cameras supplant film-based analogue photography, the resolution of LCCD arrays is accelerating while their cost declines. High resolution digital operating microscopes would provide a platform for superior augmented reality interfaces as well as extending the wavelengths of light usable by the surgeon during a given surgical procedure. Fluorescent dyes that label cortical blood flow or neuronal activity, or the aberrant blood brain barrier characteristics of a glioma, could more easily be displayed with such devices.

REAL-TIME INTRAOPERATIVE FEEDBACK

As useful as image guidance is, it is limited by the historical nature of the data that is registered to the patient anatomy. When this data is incomplete or outdated by intraoperative movements, the maps used need to be updated intraoperatively. Integration of real-time information during surgery is critical to the successful targeting of many neurosurgical procedures. Intraoperative microscopy and endoscopy provide, in essence, a continuous stream of image data that can be digitized and registered both to preoperatively obtained historical images and to the patient anatomy as it presents itself at that moment. Similarly, digitized ultrasonography provides a digital image data stream that can be used to update image registration in the event of intraoperative brain shift during resection of a subcortical tumor, or during drainage of a fluid filled cyst. Intraoperative magnetic resonance imaging and computed tomography can provide exquisite images by which to refresh registration, to assess the therapeutic success of a procedure while still in surgery, and to diagnose occult complications, such as an incipient intracerebral hemorrhage. The resection of gliomas has been augmented in some hands by the incorporation of fluorescent labels such as ALA, or by tissue analysis using optical coherence tomography. This image can be spatially registered to preoperative imaging data. Intraoperative electrophysiological data is critical to the refinement of image-guided surgical navigation in several procedures. Microelectrode recording provides the final focus for implantation of deep brain stimulating electrodes into deep subcortical structures, such as the subthalamic nucleus. Intraoperative electrocorticography is routinely used to define the epileptogenic focus surrounding a tumor or cavernous malformation that presents with medically refractory seizures, in order to optimize the therapeutic benefits of surgery upon seizure control. Intraoperative direct bipolar cortical stimulation testing defines cortical regions critical to language and motor function in patients undergoing resections of gliomas, arteriovenous malformations, cortical dysplasia, and other epileptogenic foci.

Deep brain stimulation surgery provides a clear example of how computer assistance has transformed neurosurgical practice in multiple ways. Image guidance is fundamental to accessing the target. Intraoperative electrophysiological feedback refines and selects the final implantation site. Extensive outpatient programming of the pulse generator has allowed for the tuning of this device, yielding optimization of clinical benefit for an individual patient. Finally, careful outcomes analysis of patient records has revealed a superior risk/benefit ratio for deep brain stimulation to that of stereotactic radiofrequency lesioning procedures. This has resulted in the widespread adoption of deep brain stimulation as a first line therapy for many movement disorders, despite the additional costs of hardware, device programming, and repeat surgeries for replacement of implantable pulse generators when battery exhaustion occurs. As a final consequence, the quantitative analysis of outcomes recorded in patient databases has resulted in neurosurgical techniques being applied more extensively to the management of numerous medically refractory movement disorders and affective disorders, including Parkinson's disease, generalized and focal forms of dystonia, Tourette syndrome, obsessive-compulsive disorder, and major depressive disorders.

The subdural implantation of electrode grids and strips is routinely performed when scalp electrodes fail to adequately localize an epileptogenic focus for purposes of surgical resection. A curious transitional phase of data handling is encountered at many centers performing such surgeries. The epileptogenic focus and functionally eloquent cortex is mapped onto a cartoon representation of the electrodes, derived from a two-dimensional projection cranial x-ray, and it is this drawing that guides the placement of numbered paper tickets on the cortical surface at surgery while the subdural electrode array is lifted away, thus producing a template for corticotomy. In this process of translation, digital electrophysiological information is converted to analogue spatial information, and then manually transcribed, before it is used to guide surgery. Each step along this pathway can and will benefit from computer-assisted digitalization. Once this has been accomplished, spatially registered functional mapping in the operating room will prove commonplace and fairly automated to perform.

Intraoperative imaging with operating rooms equipped with magnetic resonance and computed tomographic scanners provides a universal methodology for compensating for brain shift, assessing the completeness of resection of tumors or decompression of cysts, or confirming proper guidance of implanted catheters and deep brain stimulation electrodes. In our experience, this imaging has proven most useful for intraventricular tumors, low-grade gliomas, mesial temporal lobe resections, medial sphenoid wing meningiomas, selected pituitary macroadenomas, selected high-grade gliomas, or recurrent gliomas. Using this technology has resulted in improvement in the extent of resection in as many as one-third of the cases, avoidance of functionally eloquent parenchyma or anatomically critical structures in selected cases, provided minimally invasive approaches through narrower corridors, addressed brain shift directly, and standardized the results of extent of resection and rate of complications. Computer-assisted registration of preoperative magnetic resonance images with intraoperative magnetic resonance images, coupled with a colorized display that "fuses" the two data sets, renders obvious the degree and location of intraoperative brain shift due to surgical manipulation, as well as the extent of resection still remaining to be accomplished at a given stage during the operation. From the point of view of robotic systems engineering, intraoperative tomographic imaging provides a means of feedback with the neurosurgeon functioning to close the loop of a servo control mechanism by modifying surgical resection strategy to match the degree of surgical resection actually achieved. This servo control mechanism is the same conceptual method that was first used to robotically aim artillery at a fast moving target.

ROBOTICS

Robotics has become part of standard neurosurgical practice at this time. Passive robotic mechanisms, such as stereotactic aiming arc assemblies and frameless stereotactic articulated arms holding biopsy needles, are commonly used to access a predefined biopsy trajectory and, thereby, execute a predetermined treatment plan. Stereotactic radiosurgery represents the most developed form of this application of robotics.

The further incorporation of robotics into neurosurgical practice promises to provide several advances in our technical capabilities. The scaling of movement and force is made possible by robotic interfaces between surgeon and patient anatomy. These same devices can compensate for cardiac pulsations or respiratory motions in the display of imaging information to the surgeon, as well as tracking these movements to simplify the movement repertoire required of the operator. Haptic feedback mechanisms should allow endoscopic visualization with instruments that allow the neurosurgeon to sense tissue texture and degree of firmness during manipulation. These same methods would enhance the experience of telesurgery or tele-assisting or consultation during neurosurgical procedures in remote locations. Micromachining fabrication techniques promise a new generation of surgical instruments to match these requirements.

Passive mechanical guidance as a robotically enhanced surgical capability has been applied to the practice of stereotactic biopsies, position sensing during frameless stereotactic image-guided biopsies and craniotomies, and in the constrained movement of basic radiosurgical devices.

Active mechanical guidance allows for the execution of preplanned surgical movements. Experiments with these capabilities have been carried out using the Zeiss MKM microscope, the RoboDoc orthopedic drill for fitting hip replacement prostheses, the NeuroMate and Caspar robot-assisted surgery systems. At this time, the most successful use of active robotics in neurosurgery is that of the Elekta Gamma Knife Model 4C, which actively moves the patient's headframe from one isocenter's coordinates to those of the next isocenter in a sequence of isocenters comprising a complex radiosurgical treatment plan. This enhanced capability has made individual patient treatments faster to accomplish. Furthermore, it has provided an impetus for progressively more complex plans using larger numbers of isocenters and, thereby, producing more conformal treatment plans than previously achieved. Similarly, the Accuray CyberKnife uses a robotic arm to orient a portable linear accelerator with respect to a static patient, delivering a conformal radiosurgical treatment plan while dynamically compensating for patient breathing movements.

The analysis of clinical outcomes for stereotactic radiosurgery has led to changes in the conformality and the prescription dose of treatments, with stepwise improvement in results. This virtuous cycle has transformed clinical practice by providing an excellent addition to the clinical armamentarium for treatment of acoustic neuromas, metastatic brain and vertebral tumors, medically refractory trigeminal neuralgia, arteriovenous malformations, and cavernous sinus or cranial base meningiomas.

The National Aeronautics and Space Administration has used interactive mechanical guidance robotics in its prototype NASA Robonaut, used for extravehicular access telepresence, and by the Boeing X-45A Unmanned CAV used for reconnaissance and targeting of hostile targets. The application of this form of robotics to neurosurgery awaits the application of micromachining techniques to the fabrication of endoscopic instrumentation. The surgical microscope has revolutionized intracranial surgery for clip ligation of aneurysms for several reasons. Not only does it provide magnification and illumination, but it also effectively reduces the surgeon's interpupillary distance from more than seven centimeters to less than two centimeters. This allows for less brain retraction to be applied while preserving binocular stereoscopic vision. Because there has not been a commensurate reduction in the size of our hands, we have initially compensated by using longer, thinner, angulated microinstruments. The experience of cardiac and abdominal surgeons with the ad Vinci Surgical System (Intuitive Surgical, Inc.) has suggested a role for interactive mechanical guidance in other surgical applications. Its application to neurosurgical procedures awaits the introduction of microinstruments with "wrists" below the level of the introducing endoscopic port, such as those of the NeuRobot, allowing hand-like manipulation of tissue at the depth of the endoscopic lens intracranially. Collaboration between neurosurgeons and engineers engaged in the development of microelectromechanical systems (MEMS) will bring to bear the instruments of micromachining, microelectronics, Microsystems control, transducers, actuators, and sensors. Haptic interfaces that reproduce the sensation of touch through mechanical interfaces will serve to close the circuit of operator feedback control.

NEURAL PROSTHESES

The very technological revolution that allows for computer assistance of the neurosurgical procedure itself, in turn, allows for a more nuanced interaction with the tissue of the central nervous system. Rather than restricting the role of neurosurgical intervention to removal of offending tissue, advanced technologies allow for neurosurgical intervention that modulates, augments, or restores the normal status of nervous tissue. Reversing the vector of surgery is already augmenting the practice of neurological surgery, and promises to transform it entirely in the future. Structural prosthetics include endovascular coils for aneurysms and stents for stenoses, spinal fixation devices, and artificial discs. Electrical prosthetics include spinal cord stimulators for intractable pain, vagal nerve stimulators for epilepsy and depression, deep brain stimulators for intractable pain, movement disorders, and affective disorders, and initial efforts at functional restoration of lost bladder control, vision, and motor function. Biological prosthetics include gene therapy for gliomas, stroke, and movement disorders, stem cell transplantation for movement disorders, and tissue reconstruction techniques for nervous system tissue itself, as well as surrounding supportive structural and vascular tissue. Cochlear implants and brainstem auditory implants have become standard therapeutic interventions, with experimentation underway for auditory cortex stimulation. Retinal, visual cortex and pathway stimulation have been studied with some initial positive results. Sensorimotor cortical stimulation for restoring motor function after spinal cord injury or stroke is an active field of preclinical technological development.

SUMMARY

Computer-assisted neurosurgery has become so successful that it is rapidly becoming indistinguishable from, quite simply, neurosurgery. This trend promises to accelerate over the next several decades, bringing considerable benefit to the patients we care for.

From a pragmatic point of view, can we identify specific instances in which clinical practice has been altered by computer assistance? During craniotomies for the resection of brain tumors, this technology has led to a greater standardization within and among practitioners for the expected degree of resection and the risk of morbidity and mortality. Minimally invasive approaches are transforming the practice of cranial base surgery. This technological trend has made craniotomy for biopsy virtually obsolete in the face of frameless stereotactic techniques. Functional neurosurgery has benefited from these technologies, as deep brain stimulation surgery has become the standard of care for most cases of movement disorder surgery. Extratemporal epilepsy due to cortical dysplasia has proven especially amenable to image-guided surgical techniques that integrate electrophysiological monitoring to refine the target of resection. New surgical procedures made possible by computer assistance include minimally invasive spine surgery, endovascular procedures, resections of low-grade nonenhancing gliomas, and stereotactic radiosurgery.

A program for future research and development in this field would include:

- Electronic patient medical records
- Automatic dynamic and elastic registration
- Novel surgical instrumentation guided by augmented reality
- Real-time feedback using anatomic and functional information
- Active robotic servo control systems to amplify neurosurgical capabilities
- Outcomes analysis-driven refinement of neurosurgical interventions

It is apparent that using computer assistance in neurosurgery has begun a process that will irrevocably transform all of neurosurgical practice itself. It must be neurosurgeons themselves who provide the leadership to transcend the potentially distracting aspects of this technological revolution. What shall not change is the commitment that we, as neurosurgeons, have to the welfare of our patients.