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W Kucharczyk and M Bernstein

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Do the Benefits of Image Guidance in Neurosurgery Justify the Costs? From Stereotaxy to Intraoperative MR

Walter Kucharczyk and Mark Bernstein, *the Toronto Hospital and the University of Toronto (Ontario, Canada)*

Advances in medical imaging, together with the development of many new minimally invasive diagnostic and therapeutic techniques, have had a huge impact on the practice of neurosurgery. Image-guided, minimally invasive methods that use microinstruments, lasers, catheters, and endoscopes are achieving results comparable to or better than those obtained with traditional surgical resection. Better visibility has resulted in smaller exposures, better preservation of eloquent cortex, less extensive brain retraction, and shorter surgical recovery time. In other words, better surgery.

What Is Image-Guided Neurosurgery?

Image-guided neurosurgery includes, in the broadest sense of the phrase, all neurosurgery that is in some way assisted by the availability of images, regardless of whether the images are acquired before or during the surgery. In this broad sense, then, all neurosurgery is image guided. Moreover, modern imaging is not limited to the acquisition and display of anatomic information. Physiological, functional, and dynamic information can be obtained and incorporated into anatomic displays (1–3). These methods represent an additional layer of image guidance. For example, functional magnetic resonance (MR) imaging is now a routine procedure that identifies and displays eloquent areas of the brain. Data from functional MR imaging and positron emission tomography fused with computed tomography (CT) or MR imaging findings raise the possibility of reliable presurgical brain mapping, avoiding the large craniotomies necessary for intraoperative brain mapping. Other forms of electrophysiologic information can be superimposed on detailed anatomic maps afforded by MR imaging. Information about the state of the cerebral vasculature and cerebrospinal fluid (CSF) circulation can also be obtained from imaging technologies. For instance, flow-sensitive MR imaging can be performed in real time to determine the patency of arteries, veins, and CSF pathways.

It is our intention to be not so broad in our view, and to restrict our discussion to procedures in which imaging is performed *during surgery* (intraoperative imaging) and to procedures in which images are the *exclusive or primary guides of the surgery*. Imaging is common during surgery. A few examples are intraoperative fluoroscopy to determine the position of various surgical tools and probes relative to the vertebral column, skull base, or sella turcica; intraoperative angiography to assess the status of aneurysms and vascular malformations; and intraoperative sonography to locate difficult-to-find intraparenchymal lesions. More recently, MR imaging has been added to the neurosurgical operating room. New open-architecture MR imagers are specifically designed to permit the acquisition of MR images simultaneously with tissue manipulation, allowing true real-time image guidance for the surgeon. This has enabled traditional neurosurgical skills to be augmented with the ability to see deep to the exposed surface. In all these cases, the surgeon's traditional visual and tactile skills remain of primary importance, but the surgery is actively influenced by the imaging results.

Stereotactic neurosurgery is the prototypical example of image-guided procedures in which images are the exclusive or primary guides of the procedure and the surgeon's conventional visual and tactile skills are relegated to secondary importance. In stereotactic neurosurgery, CT or MR images obtained before surgery provide imaging data that allow the precise determination of target position relative to an external reference system (ie, the stereotactic frame). The target is then approached in a minimally invasive way based exclusively on a calculated trajectory and depth relative to the external reference acquired before surgery.

What Is the Scope of Image-Guided Neurosurgical Procedures?

The first attempts at image-guided neurosurgery in the modern era began with neuroendoscopy early this century. The first neurosurgeon to report the use of neuroendoscopy was Walter Dandy. In 1918, Dandy attempted to treat four children with hydrocephalus by avulsing the choroid plexus via a neuroendoscopic approach. He inserted a hand-held speculum through occipital trephines into the lateral ventricles, illuminating the tract by room light reflected in a head mirror. The treatment was ineffective. The instrumentation was primitive and never gained acceptance. In recent years, the neuroendoscope has been reintroduced into the neurosurgical operating room, its

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Address reprint requests to Walter Kucharczyk, MD, Department of Medical Imaging, University of Toronto, FitzGerald Bldg, Room 127, 150 College St, Toronto, Ontario, M5S 1A8 Canada.

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effectiveness made possible by advances in electronics, optics, and miniaturization. Neuroendoscopy's major uses today are for intraventricular navigation to perform third ventriculostomy and colloid cyst removal and to treat loculated hydrocephalus (4, 5). Endoscopy can also be used as an adjunct to other guidance systems, such as stereotaxy and intraoperative MR imaging (6). The navigation system provides macroscopic information about the position and alignment of the scope, while the scope provides direct vision of the tissue at the tip of the instrument. The addition of guidance systems has expanded the application of the endoscope beyond the ventricular system into the parenchyma of the brain. Intraparenchymal hematomas, cysts, abscesses, and small solid lesions have been successfully treated or palliated (7).

Perhaps the most widely practiced image-guided neurosurgical technique is frame-based stereotaxy, especially stereotactic biopsy. Stereotactic surgery was first conceived and performed early in this century for animal work by Horsley and Clark in Britain (8). The first stereotactic frame for human use was developed in the late 1940s (9), with a greater variety appearing in the 1950s. Several stereotactic frames are now commercially available.

The most frequent and important indication for application of the stereotactic technique is in the biopsy of intracranial lesions. The ideal lesion for stereotactic biopsy, as opposed to craniotomy, is a small deep lesion or one located in eloquent cortex for which risk of craniotomy and excisional biopsy is considered prohibitively high. Implicit in the decision to do a stereotactic biopsy is that cytoreduction is not required, or, if so, that it could be done during a subsequent operation. Other characteristics of lesions suited for stereotactic biopsy are diffuseness and multiplicity. With respect to patient factors, sometimes a person who under normal circumstances would benefit from an aggressive resection is better served by a stereotactic biopsy because of significant medical illness or advanced age.

Substantial benefits of stereotactic biopsy relative to conventional open biopsy include both reduced cost and reduced patient morbidity. At the Toronto Hospital, stereotactic biopsies are routinely done as day-surgery procedures. Patients arrive in the morning for preoperative imaging, undergo surgery, which on average lasts 1 hour, and then leave the hospital after 2 hours of observation. There is no overnight hospital stay. In comparison, standard craniotomy for excisional biopsy averages 3 hours, and patients are hospitalized for up to 1 week. With respect to morbidity, if similar populations were compared, the complication rate would be reduced by more than a factor of two in favor of the stereotactic biopsy (10, 11).

The reported success rate of stereotactic biopsy—that is, the frequency with which a positive and definitive diagnosis is obtained from the procedure—varies in the literature. On the basis of a metaanalysis of over 4000 stereotactic biopsies reported, one can conclude that the positive diagnosis rate is in excess of 90% (11, 12). In the case of neoplastic disease, it is unusual to miss the diagnosis, although it is not uncommon to miss the worst grade within a glioma because of sampling error. In inflammatory conditions, such as viral encephalitis and human immunodeficiency virus (HIV)-related encephalopathies, the negative or nondefinitive diagnosis rate is significantly higher owing to the relatively nonspecific nature of the inflammation in these cases. In a reported series of over 500 stereotactic biopsies done at the Toronto Hospital, the rate of achieving a definitive diagnosis was 92.5% (12). The main risk factor for failed biopsy was inflammatory lesions (12).

The reported complication rate of stereotactic biopsy also varies considerably in the literature. The accepted rate of complications appears to be about 5%, the major one being intracerebral hemorrhage. In the Toronto Hospital series, the rate was 6%; 3% resulted in neurologic devastation or death, while 3% resulted in minor or transient deficits only (11). Risk factors for hemorrhage were malignant neoplasms and inflammatory conditions, particularly in the HIV-infected population. Fortunately, the latter patients less commonly require biopsy, as the level of sophistication of serologic diagnosis and empiric therapy improves.

Other important applications of stereotactic surgery include location of a tumor for standard microsurgical removal (stereotactic craniotomy); aspiration of symptomatic cystic tumor, abscess cavities, or hematomas (13); interstitial brachytherapy (14); and for ablation therapy in the treatment of movement disorders and chronic pain.

Frame-based stereotactic systems establish and register their coordinates by means of a rigid frame attached to the cranium. A variety of alternative means can provide stereotactic guidance without the encumbrances of a frame (15–18). Positional information for frameless stereotaxy can be attained with articulated arms (ie, the surgical wand) (19), sonic devices, or optical systems. These devices track the position of a hand-held instrument and register the position of the instrument relative to the patient's head. Typically, the position and alignment of the instrument, relative to the head, are then displayed on a viewing screen. The viewing screen may be a conventional television or some more elaborate display device, such as a special set of goggles or helmet worn by the surgeon.

Frameless methods could be used as a substitute for standard frame-based stereotaxy for biopsy and drainage procedures; however, simple substitution for frame-based methods is not the major motivation for frameless systems. The problem with frame-based systems is that they cannot be used during conventional surgery, and they depend on fixing a frame to a solid, immobile structure. This limits their application to a relatively small subset of procedures. Freed of the encumbrance of a frame, frameless methods can be used as an adjunct to conventional open craniotomy and for procedures on the spine (20). Surgery for the resection of deep cerebral and skull base tumors has been the most common application of frameless stereotaxy. It has proved useful in directing the surgeon to the lesion, in defining the extent and completeness of resection, and in avoiding critical structures that are in proximity. Unlike frame-based systems, in which the decision to use or not to use stereotaxy must be made before the surgery, it is almost inevitable that if frameless systems can be made sufficiently accurate, inexpensive, and user friendly, surgeons will be inclined to use them, or at least have them available for most surgeries. However, neither frame-based nor frameless stereotaxy solves the problem of spatial inaccuracies caused by the anatomic shifts that occur after the initiation of surgery. As long as preoperative archival imaging information is the sole basis for image guidance, spatial errors during surgery will occur.

Accurate image guidance *during* surgery is clearly the objective that must be attained. Whereas this objective has been partially satisfied in a variety of ways with earlier technologies, such as flouroscopy and sonography, these techniques have not delivered the required visibility of the most critical structures in neurosurgery: the brain and spinal cord. An imaging technique that provides real-time feedback and clear visibility of the brain and spinal cord would appear to resolve this problem. Given the increasing reliance on MR imaging for neuroimaging, performing the entire surgery within an MR imager, with fresh imaging data continuously available, may be the ideal solution.

Intraoperative MR imaging is now a reality, and it is being used in an increasing variety of ways, such as with frameless stereotaxy for needle biopsies and drainage procedures. In contrast to conventional stereotaxy, intraoperative MR imaging allows direct visibility, and therefore confirmation, of needle placement in the target lesion and of the effect of any aspiration on the lesion. It is effective as a navigational aid with conventional open craniotomies and can be used to determine completeness of resection. In this application, preliminary data indicate that intraoperative MR images show residual enhancing tumor in one third of cases in which the surgeon thought “complete tumor removal” had been achieved, prompting further resection during the same surgery (M. Knauth, C. R. Wirtz, M. Forsting, et al, “Combined Use of Neuronavigation and Intraoperative MR Imaging: Does It Increase the Radicality of Surgery in Patients with Glioblastoma Multiforme,” presented at the annual meeting of the American Society of Neuroradiology, Toronto, Canada, May 1997). The most unique application of intraoperative MR imaging arises from its temperature sensitivity, which is applicable to real-time monitoring of the effects of thermal ablation therapy. Thermoablation of small tumors, using interstitial laser and other heat sources, is done at a number of centers (21) (T. Kahn, T. Harth, H-J. Schwarzmaier, et al, “Integration of Computer Simulation, Functional MRI, and Temperature Quantification for MRI-Guided Laser-Induced Interstitial Thermotherapy of Brain Tumors,” presented at the annual meeting of the International Society of Magnetic Resonance in Medicine, Vancouver, Canada, April 1997). Monitored by heat-sensitive MR sequences, thermoablative technology holds the promise of completely avoiding craniotomy and of treating the patient at the time of stereotactic biopsy.

What Are the Advantages of Image-Guided Neurosurgery?

The advantages of image guidance derive from three fundamental attributes of the technology. First, image guidance facilitates surgical planning. As imaging and related computer technologies continue to advance, the ability to accurately superimpose anatomic, physiologic, and dynamic imaging data from many different imaging techniques will increase. Information from all techniques will not be needed for each procedure, but will be selected on the basis of the information needed for the particular procedure. The images will speed the planning and the performance of the procedure while maintaining unmatched precision and safety. Second, image guidance can provide valuable intraoperative location information. This means that surgeons can navigate in the operative field faster and with more confidence, directing and defining the approach to the lesion, working around and within the lesion, integrating real-time data in the operating room, and evaluating the completeness of resection. Third, image guidance makes possible less invasive treatment methods. Long operations with general anesthesia, large incisions, and extensive bone flaps can be replaced with awake anesthesia, small incisions, and tiny bone flaps. These less invasive methods lead to less patient morbidity, shorter hospitalizations, and reduced costs.

What Are the Disadvantages of Image-Guided Neurosurgery?

Image guidance adds to the cost of procedures, although there may be off-setting savings. For some technologies, these additional costs are easily justified. For example, the cost of a $50 000 stereotactic frame is quickly recouped because use of the frame leads to minimally invasive procedures, which in turn lead to large reductions in hospital costs, perhaps by as much as a factor of five. For other technologies, these costs are very large and the savings are not so readily apparent. The most extreme example today is intraoperative MR imaging. Although costs vary according to the type of MR equipment and site location, the capital outlay for the room, MR unit, navigational system, and MR-compatible devices is typically in the $5 to $6 million range. In addition, the incremental annual operating costs, over and above that which a conventional operating room would cost, will be about $1 million, leading to a 5-year cost in the vicinity of $10 million. Even if as many as 1000 surgeries a year are performed in the unit, at least another $2000 would be added to the cost of each procedure. Yet it is not at all clear whether patient outcome will be any better, or hospital stays reduced.

Imaging equipment can add to the complexity and length of the procedure. Special training is required for the imaging personnel in the operating room and for the regular operating room staff. The imaging equipment must be set up in advance of the surgery, adding to the set-up time. During surgery, the procedure may have to be stopped, or the patient or equipment moved, to acquire a new image. Every extra step adds to the total time for the procedure.

Imaging equipment can be obstructive or cumbersome, or simply limit the surgeon's options by its very presence. Some imaging equipment may preclude the use of other surgical equipment. If a hospital does not have an MR-compatible operating microscope or ultrasonic aspirator for its new MR imaging suite, given a choice of whether to perform surgery in the MR unit or have the microscope or aspirator available in a standard operating room, the surgeon may decide to forego intraoperative MR imaging. If the surgeon prefers space to maneuver and the use of all his or her tools, some of which are not available in an MR-compatible format, the surgery will not be performed in the MR unit.

Do the Benefits of Image-Guided Neurosurgery Justify the Costs?

Doctors have an altruistic need to enhance the quality and duration of human life, no matter what the cost. When it comes to any one human being, no effort is too great and no price is too high if there is a reasonable expectation that the patient will benefit from our interventions. In this context, image guidance for neurosurgery is justified. When costs are added to the evaluation equation, our perspective is altered, and the answer to our question becomes less confident. Certainly some of the image-guided procedures, like stereotactic biopsy, have resulted in substantial improvements in morbidity *and* marked reductions in costs. Obviously, these procedures are fully justified from all perspectives.

The newer neuronavigational systems, such as articulated arms and optical trackers, are more expensive than simple stereotactic frames by a factor of three to five, costing in the range of hundreds of thousands of dollars. Also, being newer, fewer reports have been published about them. Nonetheless, our own experience indicates that these devices are tremendous location and navigational aids that have enabled reduced exposures, greater surgeon confidence, and quicker operations, which we believe lead to reduced morbidity. Although there is still no scientific evidence that the use of these devices improves patient outcome, we are of the opinion that all neurosurgical centers should have them.

It is much more difficult to assess and render an opinion about technologies that are even newer, or those for which there is only anecdotal or subjective evidence of improved outcome or effectiveness. The assessment becomes more critical when the technology is costly, such as with intraoperative MR imaging. Intraoperative MR imaging is very expensive, yet we do not know whether patient morbidity or outcome will be improved, or whether there will be any off-setting cost savings. We are of the opinion that this technology allows surgeons to be more confident about planning and executing their surgery both before and during the procedure, but there is simply no good evidence at the present of improved patient outcome or off-setting savings. Putting aside the matter of patient benefits, it is informative to examine this issue in the context of current treatment costs. The incremental cost of adding intraoperative MR imaging to every brain tumor resection would probably be about $2000 (but could be as high as $5000). On the other hand, even without the MR guidance, the combined surgical and hospital costs are about $25 000 based on typical professional fees, operating room costs, anesthesia, and a 5-day hospital stay with an intensive care bed for 1 day and a ward bed for an additional 4 days (Michael Huckman, personal communication, May 1997). An incremental cost of $2000 does not seem extraordinary, and could easily be justified if there were proof of reduced morbidity or improved outcome, or even a 1-day average reduction in hospital stay.

We believe that in the next few years there will be many studies evaluating the effectiveness of new imaging technologies. We must recognize that evaluation of effectiveness is not a precise science. Incision length, degree of resection, operating time, and length of hospitalization are poor indexes for comparison, as these parameters are subject to selection biases and differences in practice patterns. Good data on patient outcomes may take many years to acquire. Thus, it is unlikely that the cost-effectiveness of such systems will soon be convincingly and rigorously demonstrated.

Therefore, we must render an opinion without any hard facts. It is our opinion, based on the recent history of technological developments in medicine, that there will be substantial commercial and competitive pressure brought to bear on doctors to acquire this technology in their institutions. Many doctors will find this technology prohibitively expensive and adopt a wait-and-see attitude. A few institutions will implement the technology immediately and will assess its usefulness. Initially, this assessment will be subjective. Objective assessment will take longer. If the early objective assessments are favorable, in terms of reduced morbidity, improved outcome, or reduced cost, other institutions will acquire their own units.

Currently, we are in the phase of subjective assessments of intraoperative MR imaging. Our opinion is that widespread dissemination of this technology is not prudent at the present time. Notwithstanding the benefits that some patients would receive from surgery with intraoperative MR guidance, there is not yet adequate justification for widespread installation. It must be further evaluated, preferably in a small number of large neurosurgical centers with expertise in image-guided procedures. We are of the opinion that there will be some objective evidence available in 1 to 2 years about its effectiveness, and that this evidence will be favorable. Over the same period, improvements will be made in the technology, and costs will decrease as more MR units and the tools to work within them are manufactured. Computing power, which in itself is increasing at an accelerating rate, will permit even more advanced applications at ever-increasing speeds. In 2 years' time, we hope to be able to write an addendum to this article and provide references to objective studies that show that the benefits of image guidance in neurosurgery do justify the costs.

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