June Parker. *Winter Along the River*. Pastel, 26″ × 34″. Courtesy of Gallery on the Green, S. Egremont, Mass.

Obtaining real-time intraoperative images of the brain allows the surgeon to maximize the opportunity to perform optimal tumor resection.

Intraoperative Magnetic Resonance Imaging: Impact on Brain Tumor Surgery

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Background: *Refinements in the imaging of intracranial tumors assist neurosurgeons in maximizing resections in a safe manner. Intraoperative magnetic resonance imaging (iMRI) represents a recent addition to their therapeutic armamentaria.*

Methods: *The authors reviewed the development of iMRI and describe their experience with iMRI-guided resection of intracranial tumors in 112 patients. The PoleStar N-10 iMRI system was used in this series.*

Results: *Intraoperative imaging resulted in additional tumor removal in 40 (36%) of the patients. In another 35 (31%), imaging confirmed that the goals of surgery had been attained so potentially harmful dissection in and around the brain was avoided. For patients with lesions of the skull base, iMRI was possible in all but 2 patients who had a large body habitus. There was a decrease in length of hospital stay for patients who had surgery with iMRI. Lesion location did not play a role in this change. Brain tumor surgery was affected in 67% of patients. A potential for cost savings with iMRI was demonstrated.*

Conclusions: *Intraoperative imaging with MRI is the latest evolution in the increasing precision of neurosurgery. The advantages of this technology will make it a ubiquitous feature in the neurosurgical operating room.*

Introduction

The ability to safely remove a brain tumor marked the beginning of modern neurosurgery approximately 100 years ago. Since then, progress has been marked by advances in imaging, starting with plain radiographs and progressing through ventriculography and angiography, to computed tomography (CT) and magnetic resonance imaging (MRI). Improvements in surgical technology, including the operating microscope, ultrasonic aspiration, and stereotaxis, have also played a role. However, the main goal of brain tumor surgery has remained constant: to maximize resection while preserving function. Patients with benign tumors, such as meningiomas and certain low-grade gliomas, may be cured by complete resections. Length of survival most likely correlates with the extent of removal, even in patients with higher-grade

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gliomas.[1,2] The incorporation of CT and MRI scans into surgical navigation systems (sometimes referred to as "frameless stereotaxy") is an important step toward this goal. This technology allows the neurosurgeon to import a preoperative image into a computer workstation in the operating room (OR). By matching points in the image to those on the patient's head, a process known as a transformation, a navigational tool can be used to precisely point the surgeon's way to the location and borders of a brain tumor.[3] Various types of surgical navigation devices are commercially available.

The main limitation all such devices share is their reliance on preoperative images. Upon opening the skull and then the dura mater, movements or "shifts" inevitably occur, making the data derived from these images unreliable. Only intraoperative imaging can provide the updated information needed to maintain accurate navigation during surgery. What is more, such images are useful in their own right to confirm that tumor resection has been completed — a goal often not verifiable by the naked or microscope-enhanced eye — or to rule out a complication such as a hematoma.

For now and for the foreseeable future, the best means of imaging the brain is MRI. This holds true as well for intraoperative imaging, despite some recent work in using CT or ultrasound for such purposes.[4,5] Over the last decade, different means of achieving intraoperative MRI (iMRI) have come to fruition. They range from dedicated units requiring the construction of a special OR[6] to diagnostic MR suites that can be transformed into sterile surgical areas[7] and to iMRI devices designed specifically to work in neurosurgical ORs.[8,9]

While iMRI can and no doubt will become a standard tool in the general neurosurgical OR, the patients for whom iMRI would enhance surgery are those with intracranial tumors. In these patients, imaging can provide resection control and/or assure the surgeon that the operative goals have been reached, thereby avoiding possibly harmful and unnecessary additional dissection around or in the brain. This paper focuses on the use of iMRI in the surgery of patients with brain tumors.

The PoleStar N-10 iMRI System

The PoleStar N-10 (Odin Medical Technologies, Ltd, Yokne'am, Israel) is an intraoperative guidance system designed primarily for intracranial surgery in the regular OR environment. The core of the device is the magnet gantry, consisting of two vertically oriented poles 25 cm apart. Gradient coils are included on the outside of the poles. The magnetic field strength is 0.12 Tesla (T), with the 5-Gauss line measured approximately 1.5 m from the magnet center. In practice, ferromagnetic instruments may be brought as close as 25 cm from the magnet without palpable attraction. An added safety factor is that any ferromagnetic tools brought near the magnet in error will be attracted towards the nearer pole and away from the head of the patient.

For intraoperative use, the instrument is wheeled out of its iron cage and positioned under a regular OR table. The system is turned on in an adjacent room where the computer, cooler, and gradients are housed in two racks. After this point, the instrument is operated completely within the OR. The system can be controlled entirely under the surgeon's direction, although assistance from a nurse or OR technician may be helpful . The magnet gantry moves in up-down and in-out directions that are controlled by a small handheld unit. To acquire an image, a receiving coil or antenna is placed on the head of the patient and the magnet is raised to imaging position. The patient is positioned using an MRI compatible head holder with pin fixation or a simple padded bowl.

Table 1. — Characteristics of 112 Patients Undergoing iMRI-Guided Tumor Surgery

Age	
Range	3 mos – 81 yrs
Mean	47 yrs
Tumor Histology	**No. of Patients**
High-grade glioma	25
Low-grade glioma	12
Meningioma	26
Pituitary adenoma:	
Microadenoma	8
Macroadenoma	16
Schwannoma	9
Craniopharyngioma	4
Colloid cyst	3
Metastasis	2
Skull tumor	2
Pineocytoma	1
Choroid plexus papilloma	1
Other skull base	3
Tumor Location	
Frontal	28
Parietal	26
Temporal	12
Occipital	2
Sella	24
Other skull base:	
Anterior	11
Posterior	9
Surgery Type	
Craniotomy	67
Transsphenoidal	24
Other skull base:	
Craniofacial	6
Orbitozygomatic	8
Translabyrinthine	5
Transcochlear	1
Biopsy	1

The PoleStar images have a field of view (FOV) of 16 cm × 14 cm × 12 cm. With proper positioning of the magnet poles, centered at or near the volume of interest, this FOV is sufficient to image and navigate all but unusually large lesions with one scan. Various imaging sequences are available, including those with T1 or T2 weighting (W), FLAIR (flow-attenuated inversion recovery), and a sequence known as "e-steady." This sequence images the brain parenchyma in a way similar to T1W and water (including cerebrospinal fluid) as in T2W. It also has the option of 8- and 31-second acquisitions, which greatly increase the ease of use of the system. A typical imaging session will begin with an 8-second e-steady image to confirm magnet position and system function, a 1-minute T1W image without contrast, and then a 3.5-minute scan with contrast. This last sequence provides a slice thickness of 4 mm, enough for accurate surgical navigation. Thus the imaging session requires less than 5 minutes.

The infrared navigation probe is then registered by touching two divots on each magnet pole. This step may be repeated during surgery. We have verified the accuracy of the navigational system.[10] After confirming accurate registration, the magnet is lowered below the OR table and surgery begins. Imaging is repeated at the discretion of the surgeon. The magnet is raised and covered with sterile drapes as needed; a sterile coil is placed and the image(s) are acquired. Usually at least two imaging sessions are done, one before and one after surgery. Following surgery, the magnet is cleaned with water and replaced in its cage, thereby restoring the OR to regular use.

Patients and Techniques

Data on 112 patients are summarized in Table 1. The youngest patient, with a choroid plexus papilloma in the lateral ventricle, was 3 months old, and the oldest, a man with a frontal meningioma, was 81 years of age. Initially, the PoleStar N-10 was approved by the US Food and Drug Administration (FDA) for diagnostic imaging only; therefore, up to the 65th operation, patients or their families signed informed consent approved by the Institutional Review Board (IRB) of the New Jersey Medical School. Compared to other series

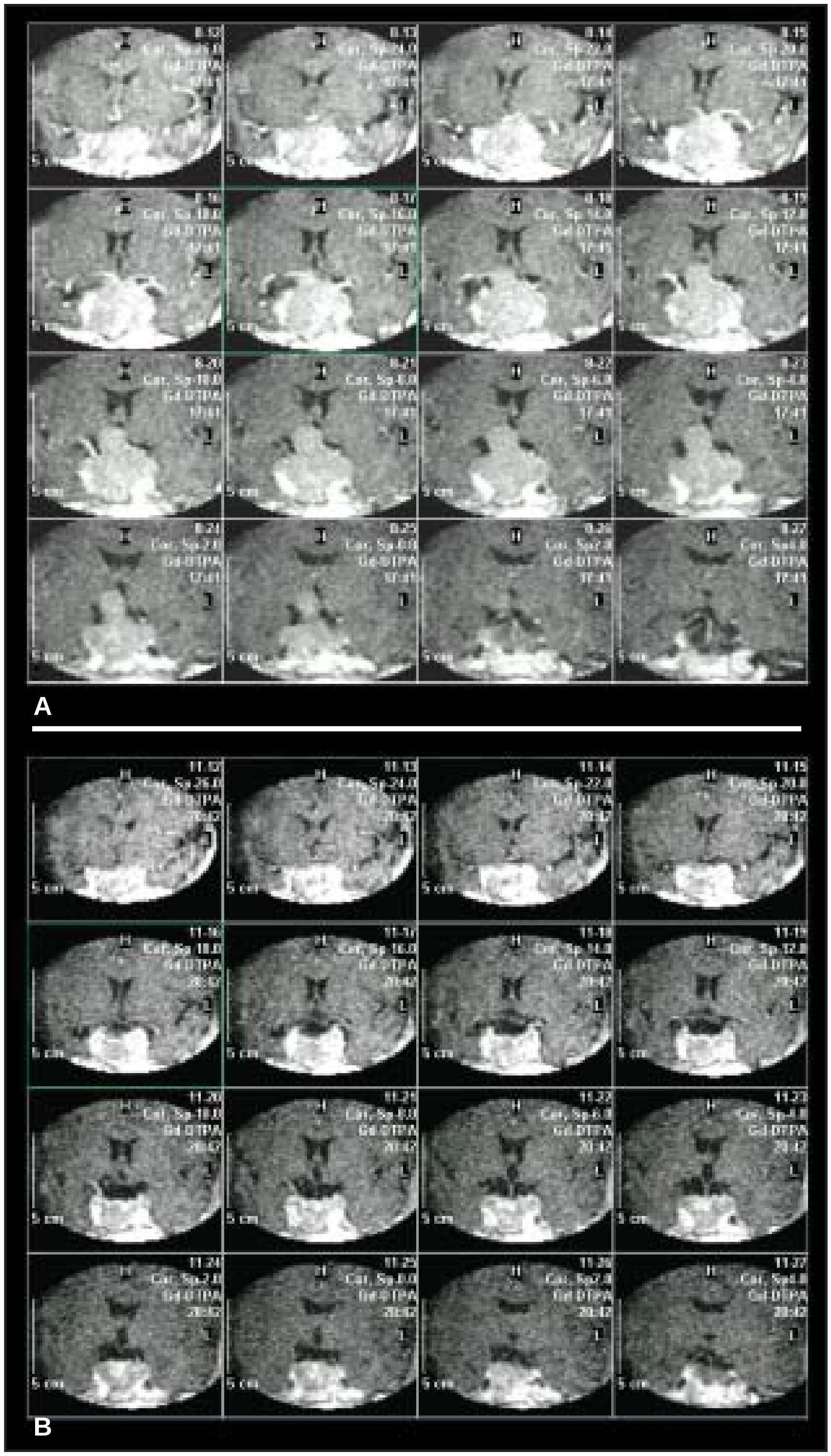


Fig 1. — Preoperative imaging demonstrating the tumor in patient 1. Preoperative coronal image obtained in the OR with pituitary macroadenoma, and (B) repeat image following resection showing chiasmal decompression with no obvious residual tumor.

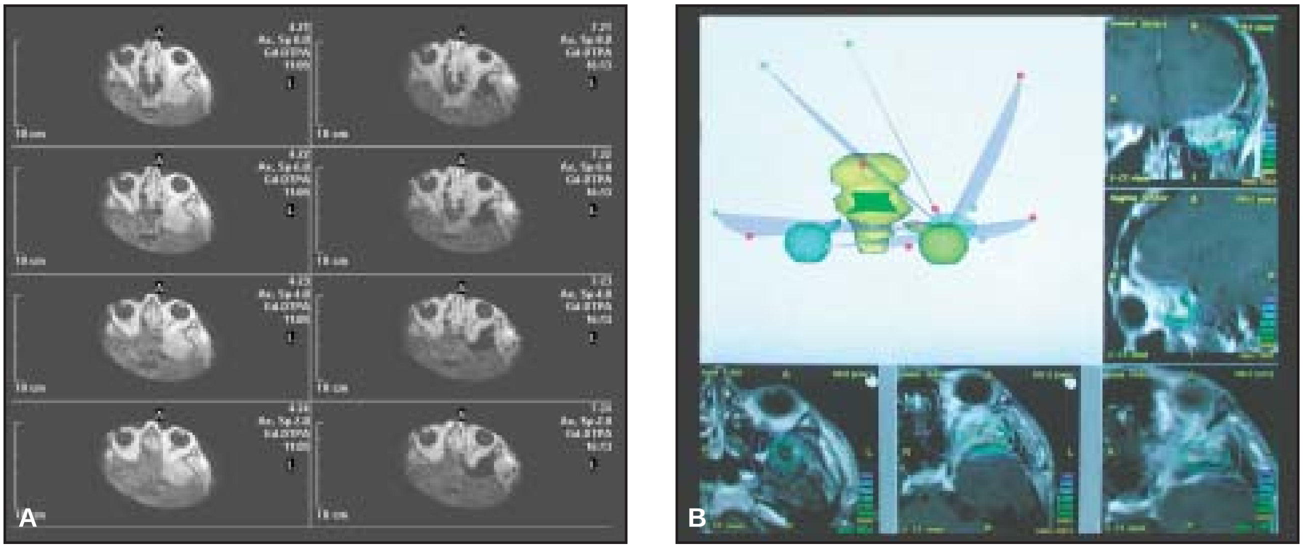


Fig 2. — (A) iMRI of patient 2 before (left panel) and after (right panel) resection. (B) Stereotactic radiosurgery on the residual tumor in the superior orbital fissure performed 8 weeks after resection.

of patients treated using iMRI, ours were more likely to have histologically benign lesions rather than gliomas.

In 2 cases, patients were positioned for surgery with the instrument, but a useful image could not be obtained, and the operations were completed without iMRI. In 2 other cases involving patients with skull base lesions, stout body habitus prevented proper magnet placement. In a 48-year-old woman with a macroprolactinoma, a fluoroscopic C-arm was used for surgical image guidance.

Case Illustrations

Patient 1

A 39-year-old man had progressive visual loss and presented with oculus sinister (OS, left eye) blindness, decreased oculus dexter (OD, right eye) visual acuity, with a right temporal field deficit in that eye. He was also found to be hypothyroid and hypogonadal, without any overproduction of pituitary hormones. Diagnostic imaging confirmed a large pituitary macroadenoma.

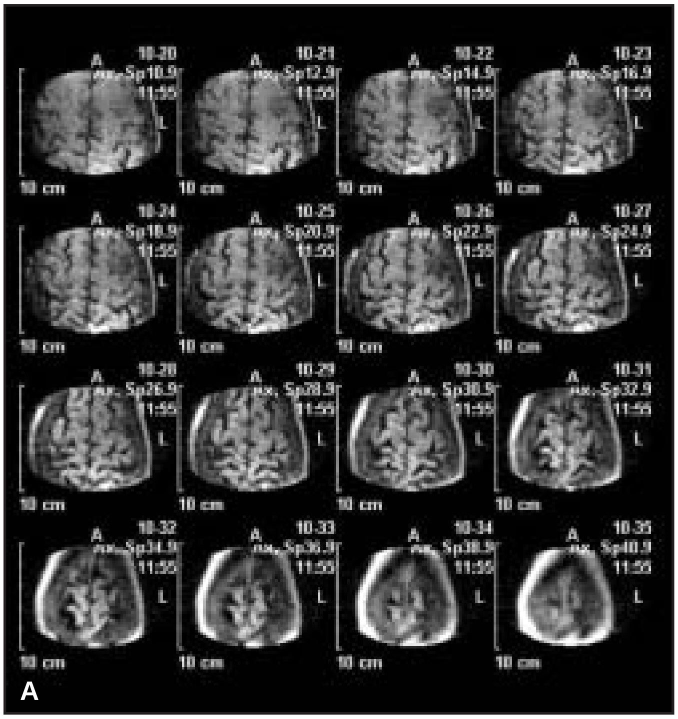
The patient was positioned supine for surgery, with his head canted slightly down to the left shoulder. The PoleStar N-10 was rotated 180º to allow for unencumbered access from below. Preoperative imaging demonstrated the tumor, and the magnet was registered for surgical navigation (Fig 1A). An endoscopic endonasal approach to the sella was performed, followed by microscope-assisted removal of the tumor. A repeat image showed chiasmal decompression with no obvious residual tumor (Fig 1B). The patient's vision OD recovered completely, and he regained 20/40 vision OS, with full fields. No clear tumor growth has been seen after 1 year of follow-up.

Patient 2

A 27-year-old man presented with proptosis and decreased vision OS. He was found to have a left lateral sphenoid wing meningioma. An orbitozygomatic craniotomy was performed with the goal of avoiding dissection in the superior orbital fissure and thus preventing inevitable ophthalmoplegia. After tumor resection, an orbital exploration repeat iMRI confirmed that the surgical goals had been achieved (Fig 2A), and the patient's vision and appearance had improved after surgery. Adjuvant stereotactic radiosurgery on the residual tumor in the superior orbital fissure was performed 8 weeks later (Fig 2B).

Patient 3

A 54-year-old right-handed woman had a right focal seizure with secondary generalization and was found to have a lesion consistent with a low-grade glioma (Fig 3A). Functional MRI indicated that the primary motor cortex was immediately posterior to the tumor. Craniotomy with iMRI guidance was done. Motor cortex stimulation confirmed that the tumor was indeed anterior to the motor cortex (Fig 3B), and dissection was begun (Fig 3C). Frozen section showed a low-grade oligodendroglioma. Initial iMRI demonstrated residual tumor. With the use of white matter stimulation to avoid injury to the corticospinal tract, more tumor was removed (Fig 3D). Repeat iMRI showed no residual tumor (Fig 3E). The patient had normal strength after surgery and was treated with adjuvant chemotherapy.



Results

The effects of imaging on surgery and related data are summarized in Table 2.

Additional Time Requirements

Additional time related to the use of iMRI did not include the time required to boot up the system or remove the magnet from the cage. That was done at the time of anesthesia induction and other standard preparations. The average added time per operation was 1.6 hours. The time needed for image acquisition was irreducible; however, later in our experience, this became less of an issue due to the availability of faster scan sequences. Some additional time was incurred due to the special positioning of both the patient and the magnet. Positioning patients in the lateral position for posterior fossa surgery took the longest time. Occasional false starts to image acquisition due to electronic noise or failure to clear ferromagnetic instruments also contributed.

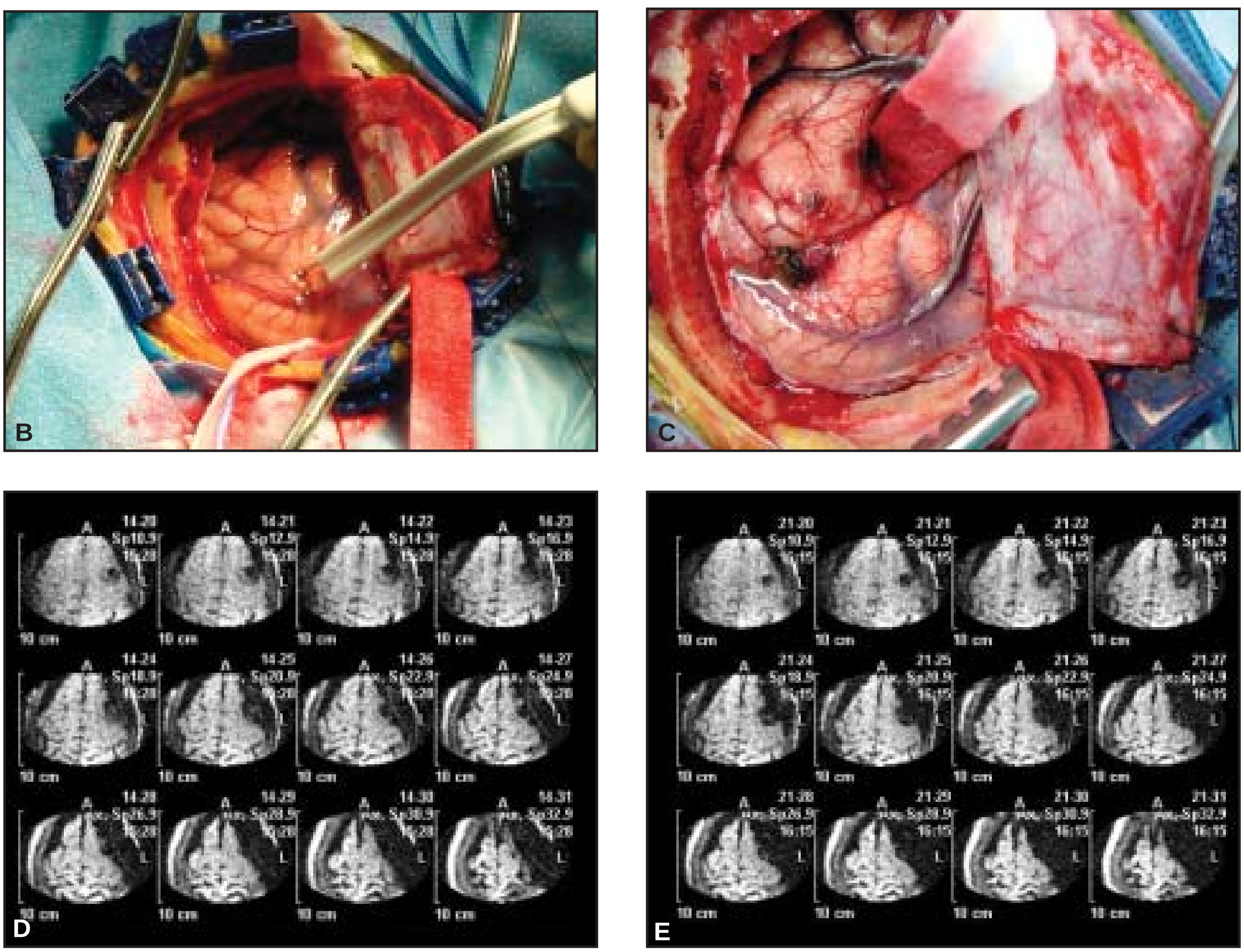


Fig 3. — (A) iMRI of patient 3 of left premotor low-grade oligodendroglioma, (B) motor cortex stimulation, and (C) tumor dissection, gyrus anterior to motor cortex. (D) Residual tumor (hypointensity) deep to resection cavity, and (E) last iMRI showing no residual tumor.

Table 2. — Surgery Data and Results of 112 Patients Undergoing iMRI-Guided Tumor Surgery

Additional Time With iMRI	
Range	.5 – 4 hrs
Mean	1.6 hrs
Number of Scan Sessions	
Range	2 – 9
Mean	3.2
Effect of Imaging on Surgery	**No. of Patients**
Additional tumors removed	40
Additional dissection avoided	35
Complications	
Postoperative hematoma	2
Cerebral infarction	1
Temporary arm weakness or numbness	2

Number of Scan Sessions

Patients underwent a minimum of two scan sessions, one preceding surgery and one following tumor removal. More images were obtained if additional tumor removal was required based on images or if a final scan was desired after closure. The largest number of scans were acquired in patients with low-grade gliomas; in these patients, progressive "shaving down" of the tumor was performed, guided by the images.

Effect on Surgery

While iMRI systems can be used for preoperative surgical navigation alone, a greater impact is achieved when the images themselves affect the course of surgery. This is most obvious when additional tumor, which otherwise would have been seen only on a postoperative scan done outside the OR, is revealed during surgery. However, no less important is the ability to ensure that the surgical goals have been reached, whether or not a complete resection was the goal. By eliminating guesswork, unnecessary further dissection — and thus the risk of injury to critical neurovascular structures — is avoided when the image confirms that the surgical goals had been achieved. Admittedly this second category is a subjective impression of the neurosurgeon.

In our experience, imaging affected tumor surgery in more than two thirds of patients, with additional tumor removal resulting slightly more often than avoidance of additional dissection.

Complications

Two patients awoke from surgery with mild weakness and numbness in one upper extremity (proximally in one patient, distally in the other). These deficits cleared within 3 days. Both patients had skull base lesions and incurred some shoulder pressure when the magnet was positioned for imaging. They may have sustained neurapraxia of the brachial plexus, although no proof of this was available. No other complications occurred related to the use of the instrument per se.

Complications developed in 3 patients by the first postoperative day. Two of these were hematomas in the surgical bed that required return to the OR with eventual good recovery. The third patient, from whom a sphenoid wing meningioma was removed, sustained a cerebral infarction that resulted in death. In each patient, a final image obtained after closure in the OR, did not reveal the complication (or secondary signs such as increased mass effect).

Costs

Data from a retrospective record analysis of the first 58 patients who had surgery with the PoleStar N-10 system were compared with 76 patients with matched diagnoses. Data obtained included length of hospital stay (LOS), length of intensive care unit stay (ICU LOS), OR time, and hospital charges (cost data was unavailable). These parameters were compared, and the statistical significance was measured, where appropriate, using Student's *t* test.

When all patients from each group were included in the analysis, we found that postoperative ICU LOS was 3.3 days for the iMRI group and 3.8 days for the non-iMRI group, but this did not approach significance (P=.21). Conversely, total LOS was 5.1 days for the iMRI patients and 9.4 days for the non-iMRI patients (P<.001). However, this dramatic decrease in LOS was not reflected in a statistically significant change in hospital charges for the two groups. As reflected in the results discussed above, OR time was increased by approximately 2 hours with use of the PoleStar N-10 in this earlier cohort of patients.

Discussion

Intraoperative Imaging

The efficacy of surgery for brain tumors has advanced with our ability to "see" inside the head, beginning in the mid 18th century with concepts of neurological localization and to the present with aids to direct operative vision such as the surgical microscope and endoscope. However, the "vision" of neurosurgeons has been enhanced mainly by the development of neuroimaging. From Roentgen's discovery

Table 3. — Selected iMRI Systems and Their Features

System	Tesla	Patient Position	Integrated Navigation?	Site	Special Instrumentation Needed?
Signa SP/i System (General Electric)	0.5	Pt inside magnet	Yes	Special suite	Yes
Magnetom (Siemens Medical Solutions)	0.2	Pt moved to magnet	No	Radiology	No
Intera (Philips Medical Systems)	1.5	Pt moved to magnet	No	Radiology	No
iMotion (IMRIS)	1.5	Magnet moved to pt	Yes	Modified OR	Yes
Sonata (Siemens Medical Solutions)	1.5	Pt moved to magnet	Yes	Regular OR	Yes
PoleStar N-10 (Odin Medical Technologies)	0.12	Magnet moved to pt	Yes	Regular OR	Yes

of radiographs in 1895 through the 1970s, the use of plain films, angiography, and pneumoencephalography was progressively refined. In that decade, however, the introduction of CT showed the brain and not merely its shadow. In the 1980s, MRI brought us non-ionizing multiplanar imaging of the brain and spinal cord. Improvements in both techniques over the last decade have yielded ever better images with shorter scan times.

Stereotactic surgery was revived in the 1980s, due in part to the marriage of CT and the stereotactic frame. Stereotactic biopsy became a common and vital tool for brain tumor management, thus making the empirical (and possibly wrong) treatment of many patients a thing of the past.[11] Frameless stereotaxy incorporated digital images to allow for surgical navigation during resection beyond merely performing a biopsy.[12,13] In less than a decade, this latter tool has become a standard part of the modern neurosurgical OR, with various vendors marketing systems that are based on either infrared imaging or, less commonly, magnetic tracking. These systems are useful for preoperative planning incisions, marking bone flaps, and navigating along the skull base. However, their reliance on preoperative data sets makes them inaccurate and potentially dangerous once brain shift has occurred. This well-known phenomenon has been described and quantified.[14]

Therefore, the impetus behind the development of intraoperative imaging has been twofold: to overcome the limitations of navigation based on preoperative images and to provide the updated images themselves. With this information, otherwise unrecognized tumor can be removed and overly aggressive surgery (ie, dissection into normal brain tissue in pursuit of presumed tumor) can be avoided. As previously noted, various imaging technologies have been adapted for use in the OR, but none match the utility of iMRI in reality and potential.

iMRI Systems

The first OR with an MRI was built at the Brigham and Women's Hospital under the neurosurgical guidance of Black and colleagues.[6] Other iMRI units have been developed and become commercially available since then. A comprehensive discussion of iMRI technology is beyond the scope of this paper, but in brief, these devices can be categorized in several ways, such as by field strength, by the manner in which the patient is brought to imaging space, and by the presence or absence of a navigation tool. Table 3 summarizes the characteristics of the best known commercially available iMRI units. Perhaps the most important distinction for neurosurgeons is the extent to which their routine is changed by iMRI. The Signa SP (GE Medical Systems, Milwaukee, Wisc) built at the Brigham and Women's Hospital requires construction of a separate suite where no ferromagnetic tools may be introduced. Other systems that adapt diagnostic MRIs with low[15] or high field strength[7] in so-called shared resource MRI facilities can be used for diagnostic as well as intraoperative imaging. The potential financial benefits of this approach are obvious.

Moving the neurosurgical suite from the OR to a radiology area poses various problems, such as maintaining sterility, arranging anesthetic coverage, and transporting instruments. Placing an iMRI in the regular OR can eliminate these problems. The group at the University of Calgary designed a 1.5T unit that is located in a shielded alcove adjacent to an OR.[16] When imaging is desired, the magnet moves on a ceiling-mounted track to in essence surround the patient. Siemens Corp, which had worked with a low-field-strength shared-resource unit,[17] is developing a dedicated 1.5T iMRI for use in an OR (R. Fahlbusch, personal communication, 2002). Each of these latter systems still requires major investments in OR infrastructure, including room shielding and strict avoidance of ferromagnetic instruments anywhere near the magnet.

Also, specialized technical help is required to operate the units. The PoleStar N-10 system was developed to overcome these difficulties and to create an iMRI that can be used by neurosurgeons on a routine basis, with no help beyond regular OR staff. However, this comes at a cost of decreased image quality and FOV when compared to a 1.5T unit, as noted above.

The ideal iMRI would provide the best possible images with the least amount of interference in the surgical routine. Thus, iMRI manufacturers are striving to improve their systems as needed, such as increasing image quality and FOV (in the case of the PoleStar N-10) and providing greater flexibility (in the case of certain high-field magnets). There is some degree of convergence developing in iMRI technology, and time will tell which system(s) will prove most effective. It seems certain, however, that MRI will remain the method of choice for neuroimaging in and out of the OR for many years to come.

iMRI in Brain Tumor Surgery

Intraoperative imaging, especially with integrated surgical navigation, has potential use in all aspects of surgery. The value of intraoperative imaging may be obvious in neurosurgery, a discipline that for decades has been based on imaging. While iMRI would be of great help in patients who need surgery (eg, for spinal disorders), the greatest impact and use to date has been on patients with brain tumors. One reason for this is purely technical; spinal imaging with iMRI has been difficult, related in part to the need to develop special receiving coils. In addition, plain fluoroscopy is an excellent way to obtain critical intraoperative information regarding spinal alignment, instrument placement, etc. The brain, on the other hand, cannot be seen on plain radiographs.

Brain tumor surgery traditionally has relied on the judgment of the surgeon to estimate the completeness of tumor resection vs the need to dissect further with the attendant risk to neurovascular structures. The limitations of this approach are well known with regard to resection of gliomas, the most common intrinsic brain tumor. Normal surrounding brain often cannot be distinguished from low-grade gliomas, especially near their edges. This is also true of high-grade tumors, although to a lesser extent. In one study, surgeons were one third as reliable as postoperative MRI at identifying residual glioma during surgery.[18] Another group operating with the Siemens 0.2T iMRI found that based on intraoperative images, additional tumor was removed from approximately one third of patients with high-grade gliomas.[19] However, the resulting increased survival (mean = 15.7 months with radical resection vs 8.6 months without) was observed mainly in patients who were younger and had a higher performance status to begin with — the selection bias that has hindered all attempts to demonstrate the benefit of surgery for patients with gliomas. The same group reported that nearly one third of their patients developed new postoperative neurological deficits, of which approximately 50% persisted after 3 months. They attributed these complications to the high percentage of patients with tumors close to eloquent areas.

Whether radical surgery for high-grade gliomas that results in new deficits is worthwhile is a matter for debate, and this applies to other tumor types as well. Another group using the Siemens system noted that 5 of 18 patients with pituitary tumors had residual lesion noted on intraoperative images.[20] In 2 of the patients, no attempt was made to remove more tumor because of the proximity of critical structures. This is not to downplay the value of iMRI in pituitary surgery, but rather to point out the need for surgical judgment, even with iMRI. At the University of Cincinnati, 2 of 3 patients undergoing transsphenoidal pituitary surgery had additional tumor removed based on iMRI.[21] At our institute, 4 of 22 patients undergoing transsphenoidal surgery had additional tumor removed based on intraoperative imaging.

Surgery for low-grade gliomas or pituitary macroadenomas may be an obvious indication for iMRI. However, these conditions occur too rarely to justify the purchase, implementation, and advocacy of iMRI for these situations alone. The true value of iMRI as a comprehensive neurosurgical navigation tool will be realized when iMRI guidance is included with any operation for a brain tumor, including craniotomies for high-grade gliomas (where the value of a gross total resection is less clear),[2] as well as surgery for convexity and parasagittal meningiomas and for metastatic tumors. While imaging may not be necessary to confirm removal of these extraaxial tumors, the capability of acquiring the stereotactic scan in the OR or omitting the need for scalp markers on a preoperative scan provides significant convenience. Concerns such as image downloads may be avoided, and the navigational information can be used to plan incisions and bone flaps. In addition, a final scan may be done to rule out a hematoma or other complication. Thus, with an acceptable image in hand, the neurosurgeon may allow a patient to emerge relatively slowly and more safely from anesthesia, without the need to "examine the patient to make sure he's okay."

The predominance of skull base operations (n = 52) is higher in our series than in other reports.[9,15,22-26] The tumors involved are extraaxial, and the need for iMRI guidance might be questioned. However, while these lesions are fixed to the skull at the base, the potential remains for shift of the overlying brain and the tumor capsule itself as resection proceeds. While cerebral tumor surgery has already been associated with a significant amount of shift,[27] in a study of brain shift measured with iMRI, we found that skull base surgery yielded similar findings. In addition, the ability to acquire images is useful. The morbidity of radical resection for patients with skull base lesions is relatively high. In many cases, a good strategy is to perform a near total resection with planned adjuvant stereotactic radiosurgery (as in patient 2 described above).[28] Intraoperative imaging can confirm that the surgical goals have been reached or that more resection is needed — before the patient is extubated and in the intensive care unit.

Advances in operative technology have made tumor resection feasible in patients who until recently may have undergone a biopsy only. However, stereotactic brain biopsy remains an important neurosurgical tool. Patients with deep-seated or multiple lesions often require a tissue diagnosis before any treatment begins.[29] In other cases, imaging alone may not differentiate between viable tumor and radiation necrosis,[30] even with such techniques as MR spectroscopy.[31] Biopsies can be performed using stereotactic frames or frameless systems, but iMRI-guided biopsy offers some distinct advantages.[24,32] Multiple targets may be selected with ease, which is a cumbersome process with a frame. Updated imaging can allay any concerns regarding registration accuracy or possible brain shifts that might occur (for instance, with drainage of a cyst). While obtaining a frozen section is still a good policy to confirm that lesional tissue has been sampled, imaging the biopsy cannula in the lesion is an added assurance that the target was reached. Also, the images can confirm that goals such as cyst drainage have been reached and that no significant hematoma resulted from the procedure.

Financial Considerations

Neurosurgeons are currently under increasing pressure to justify the purchase of new high technology equipment, which with rare exceptions is developed and sold for profit by corporations. It seems reasonable that at a minimum, iMRI should be shown to be a cost-neutral concept, which, given the large capital outlays needed to install a system, is far from certain. These range from slightly under $1 million to $5 million, with additional operating costs for the more complicated high-field-strength magnets. Hospitals may recoup these costs by increasing revenue or decreasing expenses. The former may be achieved by collecting the technical fees for acquiring and interpreting an image, provided that a radiologist (or neurosurgeon) generates a report. Until the technology becomes ubiquitous, hospitals may also attract patients who want surgery performed with state-of-the-art technology. In addition, the financial worth of iMRI can be reflected in decreased LOS (although in our series, as noted above, this did not correspond to a decrease in hospital charges).

All of the above possibilities refer to the institution that purchases an iMRI. The only way that the healthcare system as a whole can benefit financially is by decreasing expenses. The most obvious way to accomplish this is by reducing surgical complications as a result of using iMRI or by decreasing the long-term care needs of a patient. Note that in the former case, the institution and system as a whole benefit, but in the latter scenario the institution may suffer despite the benefit to society. That is, if a patient is surgically cured of a tumor, the need for adjuvant therapy is avoided and society will not have to pay for such; however, the institution will not gain the revenue that it would have earned from additional encounters with the patient. Hall et al[33] reported preliminary data indicating that in addition to decreased initial costs when using iMRI for brain surgery, the rate of repeat resection was considerably lower (0% vs 18%) for adult patients undergoing tumor resection with vs without iMRI.

Limitations of iMRI

Currently, arguments in favor of making iMRI a popular and eventually ubiquitous technology rely on so-called expert opinion. No randomized, prospective clinical trials have been done to prove its worth, and such an experiment is unlikely to take place unless a strong societal mandate for it exists. This is expensive technology that adds time to surgery (obstacles that can be overcome if the benefits are sufficiently compelling). Technical limitations include variable image quality that may not match that of a diagnostic scan, as well as the fact that certain iMRI units may not accommodate very large patients. Also, like any MRI, they may not always work. Most important, even if all goes well technically with the iMRI, neurosurgeons must still rely on their judgment during surgery. The simple presence of residual tumor on a scan may not be a reason to attempt its removal, as noted above.

Future Developments

As the technology improves, the capabilities of iMRI systems will advance. Increasingly good images will be acquired in shorter scan times. MR angiography, diffusion-weighted imaging, MR spectroscopy, and functional MRI for brain mapping will all be capable of being performed in the OR, just before or even during surgery as needed. The iMRI of the future will be a tool for physiological as well as anatomical imaging of the brain. As our understanding of brain tumor biology improves and as targeted therapies aimed at metabolic and/or physiological markers become available, advanced iMRI should play a vital role in the delivery of such treatments.

Conclusions

Advances in technology have increasingly improved the precision of intracranial surgery, and iMRI is the latest development in this field. The potential impact on the management of patients with brain tumors is obvious. By using iMRI to provide real-time information during surgery, surgical cures can be achieved that may be elusive otherwise, and serious complications can be avoided. Many centers have reported the benefits of iMRI for their patients with brain tumors, and there is some evidence that the system may be financially favorable.

While iMRI has not yet been proven conclusively to enhance outcomes in intracranial tumor surgery, evidence will become stronger as use of the technology becomes easier and more widespread. We no longer have to wait for a scan after surgery to know that we have achieved our goals, and we no longer should.

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