ARS Leksell advocated the philosophy that no technique in neurosurgery could be too refined, particularly in reference to the ability to localize lesions. In fact, it is a truism to state that the entire progression of neurosurgery has paralleled, and depended on, increasingly sophisticated neuroimaging. Random trephinations of Incan patients with epilepsy likely met with modest success, and it was only in the 19th century that Paul Broca and others challenged phrenological maxims with concepts of cortical compartmentation of function. This spawned a symbiotic relationship of neurologist and neurosurgeon, the former often guiding the latter to a presumptive operative target.

Intraoperative imaging was revolutionized by the pioneering efforts of Walter Dandy in pneumoencephalography. In 1927, the neurologist Egas Moniz and the neurosurgeon Almeida Lima performed cerebral angiography, ushering in a new era in the operative management of patients with cerebrovascular disease. Intraoperative ultrasound, both cranial and spinal, has also been successfully applied to lesion localization.

However, it was the invention of computerized tomography (CT) scanning and magnetic resonance (MR) imaging that heralded the modern epoch of neurosurgery. The use of these technologies has avoided the side effects and complications of pneumoencephalography and provided exquisite images of parenchymal disease. It was not long before the CT scanner was entrained into the operating room, as reported by Lunsford and associates. Lunsford and coworkers have suggested that CT scanning would probably remain the preeminent modality for conventional intraoperative image-guided stereotactic surgery, because of the enhanced access it provides to patients and its enhanced instrument compatibility.

The authors’ goal was to place a mobile, 1.5-tesla magnetic resonance (MR) imaging system into a neurosurgical operating room without adversely affecting established neurosurgical management. The system would help to plan accurate surgical corridors, confirm the accomplishment of operative objectives, and detect acute complications such as hemorrhage or ischemia.

The authors used an actively shielded 1.5-tesla magnet, together with 15 mtesla/m gradients, MR console computers, gradient amplifiers, a titanium, hydraulic-controlled operating table, and a radiofrequency coil that can be disassembled. The magnet is moved to and from the surgical field by using overhead crane technology. To date, the system has provided unfettered access in 46 neurosurgical patients.

In all patients, high-definition T₁- and/or T₂-weighted images were rapidly and reproducibly acquired at various stages of the surgical procedures. Eleven patients underwent craniotomy that was optimized after preincision imaging. In four patients who harbored subtotally resected tumor, intraoperative MR imaging aided the surgeon in removing the remaining tumor. Interestingly, the intraoperative administration of gadolinium demonstrated a dynamic expansion of enhancement beyond the preoperative contrast contour in patients with malignant glioma. These zones of new enhancement proved, on examination of biopsy samples, to be tumor.

The authors have demonstrated that high-quality MR images can be obtained in the operating room within reasonable time constraints. Procedures can be conducted without compromising or altering traditional neurosurgical, nursing, or anesthetic techniques. It is feasible that within the next decade intraoperative MR imaging may become the standard of care in neurosurgery.

**Key Words** • magnetic resonance imaging • neurosurgery • intraoperative imaging • radiofrequency coil

Leksell advocated the philosophy that no technique in neurosurgery could be too refined, particularly in reference to the ability to localize lesions. In fact, it is a truism to state that the entire progression of neurosurgery has paralleled, and depended on, increasingly sophisticated neuroimaging. Random trephinations of Incan patients with epilepsy likely met with modest success, and it was only in the 19th century that Paul Broca and others challenged phrenological maxims with concepts of cortical compartmentation of function. This spawned a symbiotic relationship of neurologist and neurosurgeon, the former often guiding the latter to a presumptive operative target.

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However, the use of MR imaging promised radiation-free, multiplanar images with superior spatial resolution. Intraoperative MR imaging would thus allow accurate and conservative craniotomy placement, as well as planning of safer surgical corridors. Maximum resection of tumor could be confirmed, and complications such as hemorrhage or ischemia could be detected in a timely fashion. Moreover, its use could update the archived images that plague the currently popular frameless stereotactic systems, which are unable to compensate for varying degrees
Mobile intraoperative MR system

of intraoperative brain shift and distortion. Investigators, in collaboration with industry, took up the challenge, producing systems based on one of two concepts: operating within the magnet and its associated field or moving the patient to the magnet. Black, et al., together with workers at General Electric (Milwaukee, WI), developed a 0.5-tesla, vertical, biplanar Double Doughnut configuration that has been used to aid the performance of stereotactic biopsy sampling and craniotomy, cyst drainage, and laminectomy. Although the system is seminal in concept, it may lack the field strength needed for higher quality images, functional MR imaging, and MR spectroscopy. Surgical access is somewhat limited, and the immobility of the system necessitates nonferromagnetic instrumentation, including the microscope and drill. Siemens AG (Erlangen, Germany) produced a 0.2-tesla, horizontal, biplanar intraoperative MR imaging system, the Magnetom Open, which is positioned adjacent to the operating theater. This physical separation of surgery and imaging was devised to solve the problems incurred by the General Electric Double Doughnut system, because it allows standard surgical techniques along with unfettered access. Instrument compatibility is less relevant, resulting in cost savings. However, the field strength is limited at 0.2 tesla, and patient transit may take as much as 15 minutes. It is with these concerns in mind that we developed a movable, high-field 1.5-tesla actively shielded magnet. The system allows rapid acquisition of high-quality images without the need for potentially hazardous mobilization of the patient. Surgical access to the patient remains unhindered.

Clinical Material and Methods

Imaging Magnet

Doors separate the magnet from the remainder of the operating room when not in use (Fig. 1). The superconducting 1.5-tesla magnet is now commercially available (Magnex Scientific, Abingdon, Oxon, UK) and is designed to accept acceleration and deceleration stresses when moving. To decrease fringe fields it has been actively shielded. This results in a 5-gauss line with a radial dimension of only 2.9 m, negating the need for reinforced steel in the operating room walls. The magnet subtends an inner cylindrical bore 80 cm in diameter. The installation of gradient inserts and a radiofrequency (RF) shield reduces the usable diameter to 62.1 cm. The self-shielded gradient coils generate 15 mtesla/m at 250 A with a 500-μsec rise time. Setup time is minimized with patented automatic tuning and matching of the RF coil. The magnet is 1.5 m long, which allows it to be positioned so that the part of the patient to be imaged is at the center of the bore both longitudinally and vertically. It is mobilized longitudinally on a ceiling support track by an electrical motor.

Radiofrequency Coil

The RF coil was designed to provide a high signal-to-noise ratio while maintaining complete access to the patient. The design was based on four free-standing tuned rings on the surface of a sphere that are inductively cou-
elements, stable and rapid automatic tuning and matching are accomplished. 20,21

Magnetic Resonance Imaging Console

Standard Surrey Medical Imaging Systems hardware (SMIS Ltd., Guildford, Surrey, UK) has been incorporated into the intraoperative MR imaging system. The software is being rationalized, and all computers are being converted to use Microsoft NT. The console computers, together with gradient amplifiers, are located in a room below the operating theater. A workstation remotely connected to the MR console is located in a viewing room, which is separated from the operating theater by a glass window. Acquired images are displayed on four flat active matrix monitors located both in the viewing room and on an overhead mobile arm in the operating theater. Communication between the MR operator and the surgical team is accomplished via two-way intercom.

Fig. 2. Photograph showing placement of the upper half of the RF coil onto the bottom half, which is incorporated into the operating room table. The ability to disassemble the RF coil provides free surgical access to the patient between MR examinations.

Fig. 3. Photograph showing the ceiling-mounted 1.5-tesla magnet in its imaging position.
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Operating Room Table

An important element in the success of a neurosurgical procedure is a movable operating room table that has many degrees of freedom. This table can be adjusted in height and tilted at the patient’s shoulder, waist, foot, and laterally. With the placement of an MR imaging system in the operating room, it is crucial that the table be completely MR compatible. Our table was designed and constructed from titanium and fiberglass and is sufficiently cantilevered to allow the patient’s head to be at the center of the magnet during imaging. The various movements of the table are driven hydraulically rather than by electrical motors at various times during the operation, which is necessitated by the presence of the magnetic field. The use of hydraulics provides smooth movement through all degrees of freedom. In current practice the table is returned to the horizontal position for imaging.

Operating Room

Ceiling support track beams have been attached to the building support walls. These beams are able to support the magnet, which has a weight of 4 tons. The magnet is moved into and out of the operative field by using a small electrical motor (Fig. 3). The operating theater is a standard-sized 7.58 × 10.4-m room that includes an alcove of 2.4 × 3.8 m that houses the magnet when it is not in use. For safety, the 50- and 5-gauss lines for both the docked magnet but also acts as a shield for the RF coil. When the heavy metal doors with high electrical contact with the shielded room to stop RF noise from interfering with the operation is approximately 2 minutes.

In conventional MR imaging suites, traditionally located in radiology departments, the magnet is placed in a shielded room to stop RF noise from interfering with image quality. To attenuate atmospheric RF sufficiently, heavy metal doors with high electrical contact with the door frame, and hence the rest of the room, are used. Because this would be difficult to achieve in an operating room, local RF shielding methods were developed. A tube, the outer surface of which has been sprayed with copper paint, was placed inside the gradient coil tube and connected at the non-patient end of the magnet to a copper mesh. This not only electrically closes this end of the magnet but also acts as a shield for the RF coil. When the patient has been positioned for imaging, a silver-impregnated RF tent is placed around the operating table, over the patient, and attached to the magnet, thereby establishing electrical contact between the tent and copper paint.

Imaging Studies

Prior to an MR imaging study a final safety examination is performed by the operating room charge nurse. All MR-incompatible equipment such as the operating microscope, the ultrasonic homogenizer, the high-speed air drill, and bipolar cautery are moved from the operative field to beyond the 5-gauss line. To obtain images during the surgical dissection, sterile drapes are placed over the operative field and the patient. The upper half of the RF coil is placed over the patient’s head and secured to its bottom half. The magnet bay doors are opened, the magnet is moved over the patient for imaging, and the RF tent is placed over the patient. At the completion of the study the RF tent is removed, the magnet is taken back to its alcove, the overdrapes are removed, all instrumentation is returned to the surgical field, and surgery is resumed.

Preparation for imaging, including safety inspection, draping, and positioning of the magnet requires approximately 5 minutes. A scout image (field of view [FOV] 35 cm, TR 97 msec, TE 11 msec, matrix size 256 × 256, slice thickness 10 mm, 1 average) is obtained in 25 seconds. Multislice spin-echo (FOV 25 cm, matrix size 256 × 256, slice thickness 5 mm, 2 averages) axial, coronal, or sagittal T1-weighted images (TR 500 msec, TE 13 msec) are acquired in 4.5 minutes. Currently, T2-weighted images (FOV 25 cm, matrix size 256 × 256, slice thickness 5 mm, 1 average) can be obtained with spin-echo sequences (TR 2000 msec, TE 15 msec) in 8.5 minutes. After imaging the time required to remove the magnet, RF tent, and drapes and to expose the surgical site for resumption of the operation is approximately 2 minutes.

Oil-based vitamin E capsules are placed in the proximity of a putative scalp incision to act as fiducial markers. The capsules have a characteristic, bright signal on T1-weighted images. They may also be used intracranially for interdissection imaging by covering them with sterile plastic, because they will not withstand the autoclaving process.

Results

Patient Characteristics and Safety

Table 1 presents the first 46 patients by age, gender, and pathological diagnosis. The majority of patients harbored glioma, meningioma, or vascular pathology. The remaining tumors comprised a heterogeneous group of intracranial and skull base lesions. In total, 158 MR imaging studies were performed in the 46 patients (Table 2). The studies included 67 T1, 62 T2 (after gadolinium administration), and 29 T1-weighted sequences. In all studies, the signal-to-noise ratio was sufficient to provide high-quality images.
ty images that enhanced the surgical procedure. Surgical-planning intraoperative imaging was performed prior to surgical preparation and draping, interdissection images were made at various stages of the operative procedure, and quality assurance imaging followed wound closure. There have been no adverse events related to the high magnetic field that have compromised the safety of the patient or operating room personnel. Two separate minor events occurred during positioning of the magnet: a ball-point pen was extracted from a shirt pocket and a suction stylet, left in the surgical field, was entrained into the magnet. As a result, periimaging instrument counts have been instituted and all visitors to the operating room are screened by the charge nurse and required to watch an MR safety video.

Patient body weight was restricted to 115 kg because the magnet bore could not accommodate larger patients. Similarly, constraints were placed on positioning patients in the lateral or prone positions. A new, larger bore magnet (see Discussion) has been developed to address these limitations appropriately.

Meningioma Group

Intraoperative MR imaging provided quality assurance in all 12 patients (Fig. 4). In one patient, the intraoperative imaging study revealed an unsuspected tumor that was then removed before wound closure. Interdissection or quality-assurance T₁-weighted gadolinium-enhanced studies did not demonstrate brain enhancement even when there was surgical disruption of the pia-arachnoid. Progressive brain shift was evident in 10 cases—mild in three, moderate in six, and marked in one. This reflects the removal of relatively large tumors and the loss of cerebrospinal fluid secondary to dissection within the subarachnoid space and/or basal cisterns.

Glioma Group

Of the eight low-grade gliomas, six were oligodendroglioma and two were astrocytoma. Seven of the eight high-grade neoplasms were glioblastoma multiforme, and one was anaplastic astrocytoma. Interdissection and quality-assurance studies clearly demonstrated the extent of surgical resection and the degree of brain shift associated with tissue removal and cerebrospinal fluid loss (Figs. 5 and 6). Unique to those patients with either benign or malignant glioma was the observation of progressive gadolinium enhancement beyond the confines of preoperative and surgical planning studies.

Vascular Lesions

The system has been proven particularly useful for surgical planning in the two patients with cavernous angiomas. The small volume and frequent subcortical location of the lesions made them excellent candidates for the benefits of surgical planning images (Fig. 7). In both cases the cavernomas were readily identified and resected. In the three patients with arteriovenous malformations (AVMs), the quality-assurance studies excluded the presence of intraventricular or parenchymal hemorrhage before the patient was taken from the operating room. Because MR an-

Table 2

<table>
<thead>
<tr>
<th>Imaging Sequence</th>
<th>MR Studies</th>
<th>T₁ Weighted</th>
<th>T₁-Gd Weighted</th>
<th>T₂ Weighted</th>
</tr>
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<td>surgical planning</td>
<td>70</td>
<td>27</td>
<td>29</td>
<td>14</td>
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<tr>
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<td>25</td>
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<td>2</td>
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<tr>
<td>quality assurance</td>
<td>63</td>
<td>30</td>
<td>20</td>
<td>13</td>
</tr>
<tr>
<td>total</td>
<td>158</td>
<td>67</td>
<td>62</td>
<td>29</td>
</tr>
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* Gd = gadolinium.
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Various other pathological conditions were encountered. During the resection of a small choroid plexus carcinoma related to the ependyma, the frozen section of the suspected tumor tissue showed only gliosis. With interdissection imaging we were able to define well the location of the lesion and its relationship to the site at which the biopsy sample was obtained. The tumor was subsequently removed. Interdissection imaging of the patient who harbored an olfactory nerve schwannoma revealed an unsuspected tumor that was readily resected (Figs. 8 and 9). The patient with pachymeningitis presented with headache that was associated with an extraaxial middle cranial fossa lesion. Preoperative imaging was suggestive of meningioma.

The quality-assurance studies demonstrated complete resection of all miscellaneous lesions except for residual dural enhancement in the patient with pachymeningitis.

**Fig. 5.** Surgical planning (upper row) and quality-assurance (lower row) axial T₁-weighted MR images with gadolinium enhancement obtained in a patient with glioblastoma multiforme. Note the degree of cerebral shift following resection of the tumor and the progressively enhancing border. The images were acquired in 4.5 minutes.

**Fig. 6.** Surgical planning (upper row) and interdissection (lower row) axial T₂-weighted MR images obtained in a patient with oligodendroglioma. The interdissection images demonstrate the extent of residual neoplasm. Each image set was acquired in 8.5 minutes.
Discussion

The results of this study demonstrate that high-quality MR images can be obtained in the operating room in a reasonable length of time. Furthermore, these images can be obtained without compromising or altering traditional neurosurgical, nursing, or anesthetic techniques. We are also able to perform electrophysiological studies, such as electrocorticography, which are not currently feasible when working within a magnetic field.

To date, our experience with this intraoperative MR imaging system has focused largely on tumor surgery, with resection of benign and malignant lesions in 40 cases. Five vascular malformations (three cavernomas; two AVMs) have been surgically treated, with complete removal in all cases. It was believed that operative management was significantly altered in 11 patients, resulting in minimalist surgery but maximizing technical outcomes. Placement of craniotomy was altered in many patients by up to 2 cm relative to the target lesion following applica-
tion of vitamin E capsules on the scalp prior to surgical-planning imaging studies. Craniotomies also tended to be smaller than usual, which is the case with frameless stereotaxy. Unlike the latter studies, however, we were able to update our surgical navigation. This proved to be of particular help in accounting for the brain shifts associated with positioning and dural opening. Of occasional importance was the observation of significant tumor growth in the weeks following diagnosis and scheduling of surgery; it is not unusual in the Canadian healthcare system for patients with a “stable” brain tumor to have their surgery delayed for a significant period of time. A significant number of patients were noted to have residual tumor on intraoperative imaging, resulting in reexploration to complete the resection when feasible. It is possible that aggressive cytoreductive surgery in malignant tumors improves patient survival, but our sample size and short follow-up period prevent any formal interpretation at this stage. However, total removal of benign lesions may prevent the need for reoperation or adjuvant radiosurgery. It is also very reassuring to be able to perform MR imaging that excludes the presence of hematoma in the operative bed or beyond prior to closure, particularly in the case of those patients with AVM.

Intraoperative assessment of the results of malignant glioma resection margins offers useful information regarding residual tumor volume and also provides intriguing information about the temporal profile of their contrast-enhancement characteristics. It is our experience that aggressive, extracapsular resection of meningioma does not result in peritumoral, parenchymal penetration of gadolinium, despite pial disruption. However, it is evident intraoperatively that a crescent of gadolinium advances beyond the preoperatively defined contrast limits in malignant glioma. Biopsy samples of this newly enhancing zone have thus far been histologically positive for tumor, despite gross-total resections conforming to the preoperative tumor contour. It is possible that tumor manipulation provokes release of angiogenically active molecules unique to high-grade astrocytoma and/or that tumor-infiltrated parenchyma possesses uniquely susceptible blood-brain barrier characteristics. Investigators have differentiated between immediate and delayed enhancement at the resection border, and they hypothesize that the former is a consequence of cautery. Closer characterization of this phenomenon will shed more light on the veritable industry of research regarding postoperative MR imaging for neurooncology. In one study it was noted that postsurgical enhancement, which was at its maximum intensity from postoperative Days 5 to 14 in 53% of patients, could potentially masquerade as tumor. Additionally, methemoglobin corrupted assessment of residual tumor in 35% of cases. This image interference could be minimized if intraoperative MR imaging was used. Our experience also allows us to refute the assertion that gadolinium-enhanced MR imaging performed during postoperative Days 1 to 3 avoids surgery-induced contrast enhancement and minimizes interpretative difficulties. Of great interest is the report in which 64% of patients with epilepsy developed enhancement of nonneoplastic resection bed within 17 hours of surgery. Perhaps we should exploit the intraoperative enlargement of enhancement in malignant gliomas by administering chemotherapeutic agents during surgery.

An alternative application in the clinical realm includes the use of MR angiography in assessing vessel resection in AVM surgery. The use of MR angiography at completion of carotid endarterectomy could aid in evaluation of vessel patency, and diffusion-weighted imaging could be used to assess any ischemic changes. Multinuclear MR
spectroscopy could also be used in the assessment of cerebral ischemia and central nervous system neoplasms. Indeed, it may be possible with proton MR spectroscopy to differentiate normal from neoplastic tissue.

The technical specifications of our system are such that they address many of the concerns about intraoperative imaging published by various investigators. Steinmeier, et al., have noted that a minimum of 1 hour can be added to a surgical procedure if the Magnetom Open imager is used, and in the case of pituitary adenoma, T1-weighted and turbo spin–echo image sequences required 8 and 7 minutes, respectively. With our system, calibration currently requires 5 to 10 minutes, the acquisition time of T1-weighted images (with gadolinium) is 4.5 minutes, and T2-weighted imaging requires 8.5 minutes. New software that was introduced in February 1999 has reduced calibration time dramatically to approximately 1 minute. New fast spin–echo pulse sequences will decrease the T1-weighted imaging time to 2 minutes. Additionally, fluid-attenuated inversion recovery sequences will minimize the bright water signals of irrigation saline.

Although we are able to move the magnet into the operative field within 90 seconds, its 62-cm bore does not allow facile placement of patients in the prone or lateral position. We have therefore constructed a 92-cm bore magnet (72 cm with gradient inserts), which is only 1.3 m in length. The opening has also been beveled to accommodate larger patients, maximize safety access, and allow up to 10° tilt of the operating room table during imaging. Gradient field strengths have been increased from 15 to 25 mtesla/m, which allows the use of echoplanar imaging. These changes permit the operating room to have the full range of modern MR imaging capabilities. At 1.5 tesla, MR angiography will also be of a superior quality and may be useful in vascular surgery. Although the resolution would obviously not reveal thalamostriate or basilar artery perforating vessels, diffusion-weighted imaging could rapidly reveal brain injury secondary to their occlusion and allow repositioning of the aneurysm clip prior to wound closure.

The unique two-part RF coil is highly independent of loading. It is relatively large and can be placed over the entire head and surgical field, thereby providing images that are of high quality and readily reproducible. The coil is being modified to accommodate different head positions, and it will be able to move in a vertical plane. In addition, a three-pin head holder has been developed that will be placed in the bottom half of the RF coil. The current operating room table is versatile but is hydraulic based, which requires a fairly high level of maintenance. We have thus designed, and are in the process of constructing, an operating room table that is moved by small electrical motors, much like those used in conventional tables.

We are able to report that stringent but simple safety strategies have prevented any adverse MR imaging events. All surgical personnel, including maintenance and cleaning staff, are required to study a safety video. Wooden doors are closed around the magnet when it is not in use, encouraging free operating room access during the operative part of the procedure. All instruments that must remain in the operative field at the time of imaging are MR imaging compatible, whereas others are merely moved beyond the 5-gauss line. To date, no patient has experienced any cardiorespiratory compromise during imaging. Routine anesthetic techniques with invasive monitoring are performed, and the semitransparent RF tent allows visualization of the patient.

In their report, Steinmeier, et al., concluded that: “the time needed for intraoperative neuronavigation-image updating limits this procedure to selected cases.” Lunsford wondered, “Why should we compromise the surgery to obtain the imaging?” Our contention, however, is that the high-field, mobile system we are using offers substantive benefits to neurosurgery. It is quite possible that within the next decade increasingly sophisticated intraoperative MR imaging will become the standard of care for which surgeons may strive.

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Disclaimer

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Address reprint requests to: Garnette R. Sutherland, M.D., Division of Neurosurgery, University of Calgary, 1403 29th Street N.W., Calgary, Alberta, T2N 2T9, Canada. email: garnette@dcns.ucalgary.ca.