Cranial surgery navigation aided by a compact intraoperative magnetic resonance imager

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Object. In this article the authors report on a novel, compact device for magnetic resonance (MR) imaging that has been developed for use in a standard neurosurgical operating room.

Methods. The device includes a permanent magnet with a field strength of 0.12 tesla. The poles of the magnet are vertically aligned, with a gap of 25 cm. When not in use the magnet is stored in a shielded cage in a corner of the operating room; it is easily moved into position and attaches to a regular operating table. The magnet is raised for imaging when needed and may be lowered to allow surgery to proceed unencumbered. Surgical navigation with optical and/or magnetic probes is incorporated into the system.

Twenty-five patients have undergone removal of intracranial lesions with the aid of this device. Operations included craniotomy for tumor or other lesion in 18 patients and transsphenoidal resection of tumor in seven. The number of scans ranged from two to five per surgery (average 3.4); image quality was excellent in 45%, adequate in 43%, and poor in 12%. In four patients MR imaging revealed additional tumor that was then resected; in five others visual examination of the operative field was inconclusive but complete tumor removal was confirmed on MR imaging. In 21 patients early postoperative diagnostic MR studies corroborated the findings on the final intraoperative MR image.

Using a water-covered phantom, the accuracy of the navigational tools was assessed; 120 data points were measured. The accuracy of the magnetic probe averaged 1.3 mm and 2.1 mm in the coronal and axial planes, respectively; the optical probe accuracy was 2.1 mm and 1.8 mm in those planes.

Conclusions. This device provides high-quality intraoperative imaging and accurate surgical navigation with minimal disruption in a standard neurosurgical operating room.

KEY WORDS • brain tumor • craniotomy • intraoperative magnetic resonance imaging • surgical navigation

Because of the development of digital imaging methods (first CT scanning and later MR imaging), in the last 15 years we have seen the incorporation of image-guided procedures as part of regular neurosurgical practice. Stereotactic frames have been supplemented by frameless stereotactic or surgical navigation systems. Because the tools share a reliance on preoperative data sets. Changes in intracranial topography during surgery may render inaccurate the stereotactic coordinates and surgical plans derived from these preoperative images. Intraoperative MR imaging allows us to overcome this limitation by acquiring new images during a procedure. Independent of the need for navigation, the information obtained in these images may also be of great value to confirm that the goals of surgery (for example, tumor removal) have been met and that complications (for example, hematoma) have been avoided.

To this end several intraoperative MR imaging systems have been developed. The first such unit was a 0.5-tesla superconducting unit, with two vertically oriented magnetic poles. Other low-magnetic-field designs have included a biplanar or C-arm design with a resistive 0.2-tesla magnet and a vertical gap 0.2-tesla permanent magnet. Various neurosurgeons have reported their experience with 1.5-tesla intraoperative MR imaging units, either in a modified MR imaging suite or using a mobile, 6-metric-ton magnet in a modified operating room. The concepts of different intraoperative MR imaging technologies have been elegantly summarized by Lewin.

What these devices have in common is great expense (at least several million dollars) and the need to build a special interventional MR suite, or to modify an existing suite for occasional use as an operating room. Sundry ergonomic difficulties exist, involving one or more of the following: 1) moving the patient in and out of the magnet; 2) limited access by the surgeon; 3) the inability to position patients prone or lateral; and 4) the need to move the magnet into imaging position. The PoleStar N-10 was designed to overcome these problems, and to provide neurosurgeons with an integrated system for intraoperative MR imaging and surgical navigation in a familiar operating room environment. The prototype device was tested at the Chaim Sheba Medical Center in Tel Hashomer, Israel, under the direction of Hadani and colleagues.
We report our experience with 25 patients who underwent removal of an intracranial lesion with the aid of this device.

Clinical Material and Methods

Patient Population

Surgery in which the PoleStar N-10 system was used was approved by the Institutional Review Board of the New Jersey Medical School, and all patients or their legal guardians (there were six children) signed informed consent documents. Patient data are summarized in Table 1. Craniotomies were performed in 18 patients, whereas seven underwent transsphenoidal resection of a mass. Images were assessed for quality; those deemed excellent were comparable to images obtained with a 0.5-tesla diagnostic MR imager; adequate images had poorer resolution but gave useful information; and poor images provided no useful information for the procedure.

The PoleStar N-10 System

Description. The core of the system is a permanent magnet set in two vertically aligned poles 40 cm in diameter, which are connected in a U-shaped configuration (Fig. 1); the gap between the poles is 25 cm. Certain design innovations allow excellent images to be obtained with a small device. The magnet contains no iron, allowing the field homogeneity to be maintained by the structure of the magnet itself and not by the iron casing as is usually done. Gradient coils, which are usually situated within the magnet in diagnostic MR imaging units, are located outside the magnet in this device. The location of the gradient coils allows for the 25-cm gap, resulting in improved surgical access. The magnetic field strength is 0.12 tesla. At this low field strength, image quality relies on strong gradients; therefore, this device uses gradients comparable in power to those in a diagnostic MR imager. Surface radiofrequency coils of various diameters are available, and are plugged into an antenna outlet on the magnet’s base for imaging.

The 5-G line forms a spheroid 1.5 m from the center of the magnetic field. There is essentially no magnetic attraction beyond this line; in practice ferrous instruments may be held as close as 40 cm without being attracted. The base of the magnet is mounted on wheels; when not in use the device is stored in a shielded iron cage and is easily moved into position for surgery, docking with a regular operating table, as shown in Fig. 1. In its regular configuration the magnet and base can be stored beneath the table; for transsphenoidal approaches rotating the device 180˚ allows unencumbered access.

The system’s electronics are located in an adjoining room, in which two standard 19-inch computer terminals are stationed. These are connected to the magnet and the main terminal (located in the operating room) via insulated cables. The main terminal includes a liquid crystal display monitor, a keyboard, and a remote control device that may be covered with a sterile bag and used by the surgeon during the operation. The user interface allows for the selection of image type, the acquisition of the image itself, the navigational tool, and different modes of viewing the image. Image types on the menu include T1-weighted (TR 80 msec, TE 2.8 msec) with or without contrast, T2-weighted (TR 3500 msec, TE 110 msec), and fluid-attenuated inversion recovery (TR 4500 msec, TE 90 msec, TI 1100 msec). The FOV is 12 cm wide by 16 cm high by 14 cm thick; the usual slice thickness is 4 mm but thinner cuts can be obtained with a longer acquisition time.

Implementation. Installation of the device at the New Jersey Medical School was facilitated by the existence of a neurosurgical operating room with a radiofrequency shield. An adjoining sterile supply room was readily converted into the equipment room. In the operating room itself telephone and electrical lines were filtered, incandescent lights were installed, and copper shielding placed on the wooden doors, all to minimize RFI. The iron cage used for storage of the magnet was constructed in the operating room.

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**TABLE 1**

Data in 25 patients in whom intraoperative MR imaging was used

<table>
<thead>
<tr>
<th>Lesion or Disease</th>
<th>No. of Patients</th>
</tr>
</thead>
<tbody>
<tr>
<td>glioma</td>
<td>7</td>
</tr>
<tr>
<td>pituitary adenoma</td>
<td>5</td>
</tr>
<tr>
<td>craniopharyngioma</td>
<td>3</td>
</tr>
<tr>
<td>meningioma</td>
<td>2</td>
</tr>
<tr>
<td>pineocytoma</td>
<td>1</td>
</tr>
<tr>
<td>esthesioneuroblastoma</td>
<td>1</td>
</tr>
<tr>
<td>metastasis</td>
<td>1</td>
</tr>
<tr>
<td>mucocele</td>
<td>1</td>
</tr>
<tr>
<td>inflammatory mass</td>
<td>1</td>
</tr>
<tr>
<td>cholesterol granuloma</td>
<td>1</td>
</tr>
<tr>
<td>osteogenic sarcoma</td>
<td>1</td>
</tr>
<tr>
<td>refractory seizures</td>
<td>1</td>
</tr>
<tr>
<td>location</td>
<td></td>
</tr>
<tr>
<td>skull base</td>
<td>14</td>
</tr>
<tr>
<td>frontal lobe</td>
<td>2</td>
</tr>
<tr>
<td>temporal lobe</td>
<td>4</td>
</tr>
<tr>
<td>ventricle</td>
<td>3</td>
</tr>
<tr>
<td>putamen</td>
<td>1</td>
</tr>
<tr>
<td>pineal region</td>
<td>1</td>
</tr>
</tbody>
</table>

**FIG. 1.** Photograph showing the PoleStar N-10 docked to a regular operating room table. The viewing monitor is to the right. Single asterisk designates the cabinet for magnet storage; double asterisk designates the infrared cameras for optical navigation.
room; it measures 4 ft in each dimension and thus does not have an especially large footprint in the room. Testing the integrity of the shield confirmed that there was minimal RFI at 50 dB/5 MHz, the frequency to which the device is tuned.

Once the shield integrity was verified, system installation and testing were performed. Phantom images confirmed the absence of RFI, and various operating instruments, including hand tools, air-powered drills, ultrasonic aspirators, and operating microscopes, were evaluated for magnetic attraction or the creation of RFI when in use. Room preparation and system installation were completed in approximately 2 weeks.

Features and Use During Surgery. On engagement of the main power switch in the equipment room, the computer boots up in approximately 5 minutes, allowing the system to be controlled completely from the operating room. The magnet can be removed from the iron cage and wheeled into position by one person. The operating room table is turned 180° in all cases. For supratentorial craniotomies the magnet's base will fit under the patient's head so that the surgeon and assistant may stand and work from above with complete and routine access to the surgical field. Sitting (in a regular hydraulic chair) and working with the aid of the operating microscope can easily be done, although some legroom under the table is lost. When a transsphenoidal approach or a prone position is planned for the operation, the magnet is rotated 180° as noted earlier.

Anesthesia is induced with the aid of a standard endotracheal tube and laryngoscope, intravenous catheters, arterial line, and bladder catheter. An MR-compatible anesthesia unit, including ventilator and monitor, is needed to avoid RFI and to ensure that this life-support equipment will not be affected by the MR device. The patient's head is fixed in the dedicated, MR-compatible titanium and fiberglass head holder (Fig. 2). The magnet is moved into position, and a 1-minute T₂-weighted image is obtained to confirm that the area of interest is included in the FOV. Other images may now be acquired. Typically these take 3.5 minutes to perform; therefore, if noncontrast axial and coronal images are obtained followed by images of the same planes after gadolinium injection, the preoperative imaging time will be 14 minutes.

Registration of the optical probe is then performed. Three reflector balls are located on the probe shaft and infrared-emitting cameras are positioned to allow a clear line of sight. The probe is registered by using it to touch four divots located on the magnet; software developed by the manufacturer of the imaging device aids in the registration. As long as there is no movement of the patient's head after the acquisition of the reference image, optical navigation will remain accurate. Any movement of the head will necessitate repetition of an image and re-registration, which can be performed easily through sterile drapes during surgery (Fig. 3). A magnetic navigation tool is available. This probe contains a small coil in its tip, whose location relative to the reference image is displayed on the monitor; however, it can of course be used only when the magnetic poles are raised, and cannot be autoclaved—thus it should be used only during surgery.

At this point the magnet is lowered to table height or below. Unsterile, impermeable drapes are placed over the magnet to prevent fluid seepage into the device from the operative field, and surgery is begun. Intraoperative MR imaging is performed after covering the magnetic poles with transparent sterile C-arm covers. Gadolinium is injected intravenously for contrast enhancement; the
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amount is determined by the patient’s weight. For example, a 70-kg adult receives 20 ml for a single dose, but a double-dose injection may be needed for ideal enhancement. Injection of contrast material may be repeated hourly, but we have not used it more than three times in any patient. After intraoperative imaging the poles may be lowered. We have found that lowering them halfway still allows for unencumbered access to the surgical field while maintaining the sterility of the magnet drape. The system software includes a compare function, allowing the display of images from different series, with side-by-side alignment. After the incision is closed a final image is obtained to rule out a hematoma or other complication.

Once the patient has left the operating room the system is cleaned with water and returned to the shielded cage, and the power is shut off. Although diagnostic neuroradiologists may be asked to help with image interpretation, the entire procedure is performed without the aid of radiology technicians or other specialized personnel.

Testing of Navigational Tools

A water-covered pegboard phantom was used for instrument tests. Coronal and axial T1-weighted MR images were obtained at the standard 4-mm slice thickness. Eight to ten points were measured on coronal images and six to eight points on the axial studies; the magnetic wand tip fit snugly in the pegboard holes, whereas the optical wand tip was fitted with a disc that ensured a similarly tight fit. Each study was repeated twice along with the measurements, yielding 120 data points. The distance between the displayed position of the probe tip and the center of the pegboard hole was measured with an onscreen tool.

We compared results between axial and coronal images, those acquired at the center and at the upper limit of the magnetic field, measurements in the center or periphery of the image, and those obtained using optical or magnetic probes.

Sources of Supplies and Equipment

The PoleStar N-10 system was purchased from Odin Medical Technologies, Yokneam, Israel. The Amsoco operating table was acquired from Steris, Erie, PA. The MR-compatible anesthesia unit was manufactured by Datex-Ohmeda, Madison, WI. The infrared-emitting Polaris cameras were obtained from Northern Digital, Waterloo, ON, Canada. The software for the optical probe was developed and the impermeable drapes were supplied by Odin Medical Technologies. The transparent C-arm covers were purchased from 3M Co., St. Paul, MN.

The Ojemann bipolar stimulator was acquired from Radiomics, Burlington, MA. The MR-compatible operating microscope was purchased from Leica, and the ultrasonic aspirator from Sharplan, both located in Allendale, NJ. The self-retaining brain retractors were obtained from SEC, San Carlos, CA.

Results

All but three patients were placed supine, with rotation and/or extension of the head done as needed. Prone (two patients) and lateral positions (one patient) were accomplished without undue difficulty. Evoked potential and/or cranial nerve monitoring were performed in three patients by using platinum electrodes. The quality of evoked potential readings, electromyography, and imaging was unaffected. One patient with a left-sided temporal tumor underwent awake language mapping with the aid of an Ojemann bipolar stimulator.

The surgical instruments used were regular (attracted to the magnet), MR imaging–safe (no attraction but creating a magnetic artifact on imaging), or MR-compatible (no magnetic attraction or artifact). With the magnetic poles lowered, regular instruments were used without difficulty. These included such hand tools as scalpels, scissors, and peristeal elevators. The MR imaging–safe instruments used included an operating microscope and an ultrasonic aspirator. Although regular instruments can be used exclusively, we found it convenient to use at least some MR-compatible implements—for instance, towel clips and Weitlaner retractors for scalp retraction, a titanium nasal speculum, and self-retaining brain retractors. Transition time to imaging (including movement of the magnet and turning off electrical equipment) took approximately 1 minute.

The number of image acquisitions ranged from two to five (mean 3.4); T1-weighted imaging with contrast addition was the most commonly used modality. Use of this new modality added from 1 to 4 hours per procedure; for the first 10 operations this averaged 2.6 hours, but decreased to 1.7 hours for the last 15 procedures. Undoubtedly, some of this increased time was related to the fact that this was a new device, and changes to the headholder equipment and positioning techniques have also contributed to the relatively shorter times in the patients treated more recently. Image quality was rated excellent in 45% of cases, adequate in 45%, and poor in 12%; it has tended to be better in our more recently treated patients due to the use of larger surface coils and other technical improvements (surgical and imaging data summarized in Table 2).

In four patients MR imaging revealed additional tumor that was then resected (for example, in Cases 1 and 2, which are described later); in five others visual examination of the operative field was inconclusive but complete tumor removal was confirmed on the intraoperative image (for example, in Case 3). In all 21 patients who underwent early postoperative diagnostic MR imaging, the findings on the final intraoperative MR image were corroborated.

There were no complications associated with the use of the PoleStar MR system.

Case Illustrations

Case 1: Cerebral Glioma

In 1997, this patient, a 36-year-old right-handed man, had received a diagnosis of a left frontal Grade 2 astrocytoma according to the World Health Organization scale.15 After stereotactic biopsy sampling was performed he had been treated with external beam radiation therapy (54 Gy in 30 fractions). He had returned to work but follow-up diagnostic MR imaging then revealed a new, enhancing mass in the left frontal lobe (Fig. 4 upper left). At surgery the patient was placed supine, and a preoperative MR image with gadolinium contrast was obtained. A left frontal
craniotomy was positioned over the mass with the aid of the optical navigation tool. Tumor resection was accomplished using a standard microscope and a regular ultrasonic aspirator. Serial intraoperative MR images were obtained, and resection was monitored using the compare function until no residual contrast enhancement was seen in the tumor bed (Fig. 4 lower). Histological findings on frozen sections were consistent with a Grade 3 astrocytoma, and bis-chloroethyl-nitrosourea-containing polymer wafers were placed in the area of the tumor. The patient remained neurologically intact and was discharged home on the 2nd postoperative day; diagnostic MR imaging demonstrated no residual tumor (Fig. 4 upper right).

Case 2: Pilocytic Astrocytoma

This 2-year-old girl had undergone biopsy sampling of a posterior fossa lesion at another institution, with inconclusive results. She had developed dysphagia and her motor milestones were delayed. Axial diagnostic MR imaging revealed a mass arising from the brainstem that featured a large exophytic component (Fig. 5 left). The patient was placed prone for surgery, and coronal intraoperative MR images were acquired (Fig. 6 left). When tumor removal was thought to be complete a new coronal scan still showed a mass (Fig. 6 right); this was resected and found to be a pilocytic astrocytoma. Postoperative diagnostic MR imaging confirmed complete resection (Fig. 5 right). After surgery the patient had a mild right hemiparesis; however, within 2 months she was neurologically intact.

Case 3: Pineal Region Tumor

This 32-year-old woman was admitted after complaining of headaches; she was neurologically intact. Diagnostic MR imaging revealed a pineal region mass and obstructive hydrocephalus, for which a ventriculoperitoneal shunt was placed. Serum and cerebrospinal fluid markers and cytological findings were unremarkable. Two weeks after shunt placement the patient underwent a posterior fossa craniotomy, for which she was placed prone with her neck flexed in the dedicated head holder. Coronal intraoperative MR imaging demonstrated the tumor and overlying internal cerebral veins (Fig. 7 upper). After resection we were concerned that there might be residual tumor, but complete resection was demonstrated on contrast-enhanced intraoperative MR imaging (Fig. 7 lower) and possible brainstem injury was avoided. Postoperative diagnostic MR imaging confirmed complete removal; pathological examination of tumor tissue revealed a pilocytic astrocytoma. The patient had a gaze paresis that resolved after 4 weeks, and otherwise remains intact.

Navigational Accuracy

All groups of data points had a near-gaussian distribution around the mean. In the coronal plane, accuracy with the magnetic probe ranged from 0 to 2.7 mm (mean 1.3 ± 1 mm, SD), and with the optical probe it was 0.3 to 4.3 mm (mean 2.1 ± 1.2 mm, SD). Accuracy with the magnetic probe in the axial plane ranged from 0 to 3.8 mm (mean 2.1 ± 1.1 mm, SD) and from 0.5 to 4.3 mm (mean 1.8 ± 1 mm, SD) for the optical probe. Images obtained at the upper border of the magnetic field provided navigational accuracy similar to those obtained in the center of the field (1.7 ± 1 mm compared with 1.9 ± 1.1 mm [SD], respectively). Measurements in the center and periphery of the image yielded mean errors of 1.8 ± 1 mm [SD] for both). None of these differences were significant according to the Student t-test, all having probability values of less than 0.1. Data are summarized in Table 3.

Discussion

Decreases in the need for guesswork have marked the progress of neurosurgery. Neurological localization, plain x-ray films, ventriculography, angiography, CT and MR studies, stereotactic frames and frameless stereotaxy—all of these advances not only have improved our ability to diagnose intracranial lesions but have made brain surgery ever more precise. Intraoperative imaging has been a part of the neurosurgical operating room in the form of C-arm fluoroscopy. The first use of digital imaging during neurosurgery was with CT scanning,17 and efforts to extend the use of this modality in the operating room continue.12 Nonetheless, enthusiasm for this technology has been limited by several factors, most importantly the often inadequate soft-tissue contrast obtained with CT scanning. Other concerns have included its use of ionizing radiation; ergonomic issues such as constraints on patient positioning; and the costs of installing and running an intraoperative CT scanner, including the expense involved with hiring a dedicated CT technologist.

Intraoperative MR imaging units have been developed to overcome the limitations of CT scanning. The impetus behind these efforts has been twofold: first, to provide updated imaging during surgery by using the best available technology; and second, to facilitate improved surgical navigation. The latter need is a result of the reliance of frameless stereotactic systems on preoperative data sets. Brain shift during surgery has been measured in a number of studies, and has been found to be as much as 1 cm, es-

Table 2: Surgical and Imaging Data in 25 Patients With Intracranial Lesions

<table>
<thead>
<tr>
<th>Factor</th>
<th>Value</th>
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<tbody>
<tr>
<td>surgical procedure</td>
<td>18</td>
</tr>
<tr>
<td>craniotomy</td>
<td>7</td>
</tr>
<tr>
<td>transsphenoidal resection</td>
<td>22</td>
</tr>
<tr>
<td>patient position</td>
<td>2</td>
</tr>
<tr>
<td>supine</td>
<td>1</td>
</tr>
<tr>
<td>prone</td>
<td>2</td>
</tr>
<tr>
<td>lateral</td>
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</tr>
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<td>no. of images</td>
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</tr>
<tr>
<td>mean</td>
<td>3.4</td>
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<tr>
<td>time added by use of device (hrs)</td>
<td>1–4</td>
</tr>
<tr>
<td>mean</td>
<td>2.0</td>
</tr>
<tr>
<td>overall</td>
<td>2.6</td>
</tr>
<tr>
<td>1st 10 procedures</td>
<td>1.7</td>
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<tr>
<td>last 15 procedures</td>
<td>1.7</td>
</tr>
<tr>
<td>image quality (%)</td>
<td>excellent 45, adequate 43, poor 12</td>
</tr>
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</table>
especially in the direction of gravity. Frameless stereotactic devices have a measurable error, which is related to intrinsic error in the localizer, imaging techniques, and intraoperative factors such as head movement; when brain shift is added to these factors the possibility of a clinically significant error becomes a serious consideration. Even for lesions that are anatomically fixed and therefore not prone to movement during resection—for example, cer-
tain skull base tumors—shifting of the surrounding brain as the mass is debulked may render hazardous the use of a preoperative image for navigation.

The ideal intraoperative MR imager would do the following: 1) provide images as good as the best diagnostic MR imager; 2) not interfere with the regular operating room environment in terms of instrumentation, patient positioning, or surgical access; 3) include an accurate navigational tool; 4) be usable in all (neuro)surgical procedures; and 5) add little or no time to the duration of surgery. In reality, systems have to compromise on these goals, to varying degrees.

**Intraoperative MR Imaging Systems With Low-Field-Strength Magnets**

The first intraoperative MR imaging unit (Signa SP) was developed by General Electric Medical Systems (Milwaukee, WI) and was installed at the Brigham and Women’s Hospital in Boston. First described by Black, et al., the device has also become known as the “double donut” design. It consists of a 0.5-tesla superconducting magnet with two vertically oriented poles separated by a 56-cm gap, which allows two surgeons to stand, one on either side of the table. The system includes an infrared light-emitting diode–based navigational tool. The group at the Brigham and Women’s Hospital has reported performing more than 200 craniotomies in this unit, including 60 procedures for tumor, which have been described in some detail. Using this device added approximately 1 hour to surgery, and the authors noted that in more than one third of their cases MR imaging revealed residual tumor requiring further resection. The system may be used for spinal surgery and for such nonneurosurgical applications as endoscopic sinus surgery. Image quality with this system is not as good as diagnostic MR imaging. The Signa SP costs approximately the same as a high-field diagnostic MR imager. A special surgical suite with an iron shield must be constructed for its use, and all equipment must be MR-compatible, which brings the cost of installation to nearly $6 million. Ergonomically, the vertical gap provides restricted access to the surgical field (M Hadani, personal communication, 2000).

A different concept was used by Siemens (Erlangen, Germany) in developing the Magnetom Open, a 0.2-tesla resistive intraoperative MR imager with a biplanar or C-arm design. In this system, surgery is performed in a regular operating room, and when imaging is indicated the patient is moved into an adjoining, separate suite containing the magnet. The group in Erlangen reported that they performed some surgery in the MR imaging suite, which was a relatively short distance from the magnet, thus reducing the transport time from 15 minutes to 2 minutes. They found this especially useful for transsphenoidal pituitary surgery. Of 18 such cases, residual tumor was seen in five; in two patients no additional tumor was removed to avoid injury to the cavernous sinus in one patient and to the optic chiasm in the other. This report from a renowned center of pituitary surgery points out the obvious but equally important fact that intraoperative MR imaging, just like any other technology, is no substitute for sound neurosurgical judgment.

Data on the use of the Magnetom Open has also come from the Heidelberg group, who described their experience in treating 97 patients with gliomas, including 68 high-grade tumors. Image quality was good or fair in 85.5% of MR studies; intraoperative MR imaging revealed residual tumor in 62.1% of patients with high-grade gliomas and 41.4% with low-grade lesions; after additional surgery, tumor was purposely left in 19.7% of the
former group and 15.4% of the latter. Of the entire group, “nearly one-third of the patients experienced postoperative neurological deterioration”;25 the authors acknowledge that additional resection near eloquent brain areas, prompted by intraoperative scan results, may have led to this seemingly high rate of new deficits after surgery. Patients with high-grade gliomas in whom no tumor was seen on postoperative diagnostic MR imaging had a median survival of 15.7 months compared with 8.6 months for those in whom residual tumor was present; these patients also tended to be younger and to have a higher Karnofsky Performance Scale score.14

Rubino, et al.,26 expanded the notion of the “fringe fields” (designated Area B by the Erlangen group) to do a full gamut of procedures with the Magnetom Open. Surgery was performed in a modified MR suite, and the MR table was rotated away from the magnet to allow the use of regular instrumentation. This setup did not permit surgical navigation; because patients were placed on the imager table there was no ability to reposition using table controls, and a special foam head holder was made for use on the MR table.

At the University of Toronto, a 0.2-tesla intraoperative MR imager with a 46-cm vertical gap was developed.2 Patients are moved between the magnetic poles for image acquisition; in the out position conventional surgical tools

FIG. 7. Upper Two Rows: Intraoperative MR images obtained after patient positioning; a radiofrequency artifact is present but does not interfere with visualization of the tumor. Lower Two Rows: Images obtained after resection confirming the absence of residual tumor.
Intraoperative MR Imaging System With High Field Strength

The systems described earlier and our system all contain low-field-strength magnets, with some inevitable compromise in image quality and system versatility. Hall, et al., have performed surgery aided by a specially designed superconducting 1.5-tesla MR imager (Philips Medical Systems, Best, The Netherlands) in a modified MR imaging suite. These authors used MR-compatible stereotactic frames but no frameless system. The falloff of the magnetic field allows surgery to be done with regular instruments outside the 5-G line, which is several meters from the magnet; patients are moved into the machine as needed. The typical time needed for transition from surgery to imaging is 3 to 5 minutes. Two patients of 101 developed infections; two developed hemiparesis after craniotomy for tumor removal; and in one patient a hematoma developed 3 hours postsurgery (after the final intraoperative image). Magnetic resonance spectroscopy and functional MR imaging were also reported. The images were comparable to those obtained with high-quality diagnostic MR imaging.

A different concept for high-field-strength MR imaging has been developed at the University of Calgary; the scanner moves to the patient, rather than the reverse. In its latest iteration, the magnet is a 6-metric-ton superconducting 1.5-tesla device that moves on a ceiling track from an adjacent alcove into the operating room (Innovative Magnetic Resonance Imaging Systems, Winnipeg, MB, Canada). Special operating room modifications (besides the shield) included a titanium table, a head holder, and a copper radiofrequency shield that is placed over the patient during imaging. This system allows for a full range of patient positions, the use of regular equipment, and the acquisition of diagnostic-quality images. A commercially available, infrared-based surgical navigation device (BrainLAB, Heimstetten, Germany) was used, modified only by the inclusion of a newly designed array of intraoperative fiducial markers. No complications were reported after surgery in 101 patients.

The PoleStar N-10

The aforementioned devices represent various compromises with the ideal intraoperative MR imager. They may have one or more of the following drawbacks: 1) suboptimal image quality; 2) require major operating room modification, purchase of new instrumentation sets, and/or moving the operating room to an MR imaging suite; 3) lack a surgical navigation tool; 4) provide limited access to the field by the surgeon and assistant; 5) may not allow certain patient positions to be used; or 6) cannot be operated by the surgeon.

The system we used was designed to improve on these limitations. The image quality is better than that provided by other low-field-strength systems. It is meant to be used in a regular operating room to which relatively small changes are necessary; installation of a radiofrequency shield can be accomplished without major disruption to surrounding rooms, and other modifications, such as preparation of the equipment room, can be completed within several weeks. Surgery can be performed using only regular instruments, if necessary. A reliable navigation system is integrated with this device, allowing reregistration during the surgery, along with updated images. Other than the loss of a small amount of legroom under the operating table, access to the patient is unencumbered. Patients may be positioned in any way except sitting. Purchase and installation (including a set of MR-compatible instruments) costs less than $1 million. No expenditure for technician support is needed to maintain and run the equipment, and the additional time involved in its use during surgery is comparable to that required for other intraoperative MR imaging devices.

The system in its current form has certain disadvantages; high image quality is obtained at the expense of a full FOV, although the actual surgical field is always smaller than that covered by the image. Oblique views, currently unavailable, may permit the use of integrated biopsy tools. As with other low-field-strength units, functional MR imaging, MR spectroscopy, or other physiological applications cannot be used. The magnetic navigation probe can be used only when the poles are elevated; the optical tool, although accurate, would be greatly improved by the addition of a dynamic reference frame that will maintain registration even if the patient is moved. The 25-cm gap between the magnet poles limits the use of this device to patients with lesions located just below the skull base and up; thus it is not suitable for spinal surgery.

Conclusions

This intraoperative MR system, which was developed...
Cranial surgery aided by a compact magnetic resonance imager

for cranial surgery, provides high-quality intraoperative imaging and accurate surgical navigation with minimal disruption to a standard neurosurgical operating room. Technical improvements will bring it closer to the intraoperative MR imaging ideal. The role of this and other intraoperative MR imaging units will be defined in the coming years as neurosurgeons gain and report further experience. Technical questions (such as timing of contrast injection, interpretation of contrast enhancement, or optimal image sequences) and clinical issues (for example, patient selection and outcomes analysis) will need to be resolved. This and other intraoperative MR imaging systems represent a new phase in the advancement of intraoperative neurosurgical information-gathering devices.

Disclosure

None of the authors has a financial interest in the PoleStar N-10 or in Odin Medical Technologies.

References


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