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Intraoperative magnetic resonance imaging at 0.12 T: is it enough?

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Intraoperative MRI (iMRI) was first demonstrated by Black and his group [1] at the Brigham and Women's Hospital. With partners at General Electric Medical Systems (Waukesha, Wisconsin), a 0.5-T magnet was built in a specially designed operating room (OR) suite apart from the OR complex. Other investigators and manufacturers followed in their wake, using magnets of varying strengths and with different requirements for alteration of the OR to accommodate a powerful magnet [2,3] or of a radiology suite to become an occasional OR [4,5].

These brilliant technical innovations did share certain limitations from the perspective of the neurosurgeon. They moved the OR to an unfamiliar location or provided limited access to the surgical field, required complicated patient movements to allow for intraoperative imaging, had limited patient positions available, necessitated the manufacture of MRI-compatible instrumentation, or required special personnel to operate the systems. In addition, costs of these iMRI systems and their installation typically reached at least several million dollars. The PoleStar system was designed as a tool for intracranial neurosurgery, in conjunction with neurosurgeons, to make iMRI an accessible technique for anyone performing brain surgery.

PoleStar intraoperative MRI

Specifications

The PoleStar N-10 (Odin Medical Technologies [OMT], Yokne'am, Israel) is built around a 0.12-T permanent magnet [6]. The magnet poles are vertically oriented with a gap of 25 cm. The gradient coils are located on the outside of the magnet, allowing the system to be parked under a standard OR table (Fig. 1). These gradients, equivalent in power to those in diagnostic MRI (dMRI), allow the PoleStar N-10 to provide useful images despite the low magnet strength. A limited field of view (FOV) of 16 cm × 14 cm × 14 cm, enough to encompass essentially any surgical field in practice, is imaged. The gantry (magnet and gradient coils) is moved by electrical motors controlled with a simple handheld device. The MRI computer, cooler, and gradients are in an adjacent room (a small storage room converted for this purpose).

An optical surgical navigation tool is integrated with the PoleStar N-10. Infrared-emitting cameras track passive reflecting spheres on a bayonet-shaped probe, similar to those used in commercially available "frameless stereotaxy" [7]. The magnet is automatically registered with the aid of a magnetic reference frame (MRF) that is attached to one of the magnet poles. A patient reference frame (PRF) is secured to the dedicated MRI-compatible head holder. By thus maintaining a known spatial relation between the surgical field and the acquired image, the navigation probe continues to be spatially accurate throughout the procedure. Movement of the patient's head relative to the head holder renders the navigation

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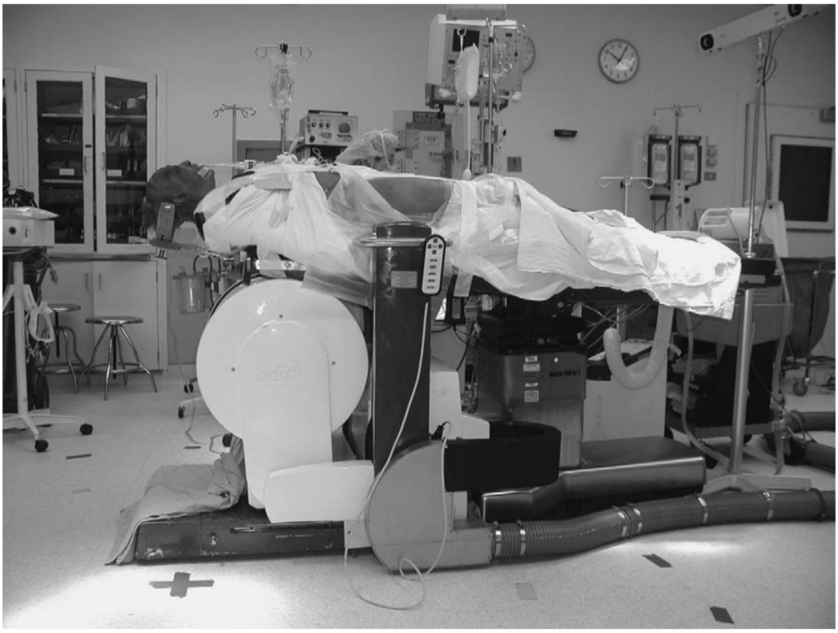

Fig. 1. PoleStar N-10 under operating room table.

accurate, in which case, repeat imaging and securing of the head holder corrects the problem.

The 5-G line of the PoleStar N-10 forms a near-hemisphere with a radius of 1.5 m, slightly elongated in the axis of the magnet poles. In practice, ferromagnetic instruments (eg, periosteal elevators or other hand tools) may be brought within 20 cm or so of the magnet poles without a significant attraction being felt. If, by any chance, an instrument is attracted to the magnet, it is pulled to the poles (ie, away from the patient's head). More complex tools, such as high-speed drills, operating microscopes, and ultrasonic aspirators, may be used in routine fashion. It is recommended that equipment needed for life support be MRI-compatible (eg, anesthesia machine, monitors), however. In most centers, the anesthesiologists have experience with such equipment from use in dMRI scanners.

No magnetic OR shielding is needed for the PoleStar N-10 thanks to the low magnetic field strength. Conversely, radiofrequency shielding

Table 1
Specifications of the PoleStar N-10 and N-20 units

Model Parameter	Odin PoleStar N-10	Odin PoleStar N-20
Magnet type	Permanent	Permanent
Field strength	0.12 T	0.12 T
5-G fringe field (radial/axial, m)	1.5	2.2
Shimming	Passive, active	Passive, active
Gradient subsystem		
Strength (mT/m)	25	22
Rise time to 20 mT/m/ms	<1	<1
Gradient cooling	Coolant circulation	Coolant circulation
FOV, ellipsoid (diameters, cm)	10 × 15	20 × 15
Magnets gap (cm)	25	27
Front end (gantry and magnet) weight (kg)	450	670
Gantry-driving mechanism	Electrical	Combined, electrical and hydraulic
Front end low position height (cm)	95	103
Gap between gradient coils (shoulders, cm)	48	58

is necessary to allow for imaging without radiofrequency interference (RFI) from unfiltered electrical sources. An innovative solution devised by OMT uses a pneumatically operated local shield, which is closed over the patient and magnet for imaging and left opened most of the time for surgery. This method obviates the need for potentially costly room shielding and permits more routine work flow throughout iMRI-guided surgery [8].

Early experience with the PoleStar N-10, however favorable overall, exposed some limitations of the system. The limited FOV was disorienting to some surgeons; the 25-cm magnet gap made lateral head turning problematic; and the posterior fossa was difficult to image, with only the cerebellopontine angle visible with the patient in a lateral decubitus position. In general, positioning was often a chore; the anterior skull base could be hard to image, especially in patients with large shoulders, and the image quality could be variable, especially when imaging during surgery [9]. To address these concerns, OMT has recently released a newer version of their iMRI, the PoleStar N-20. This new system has a 0.15-T magnet. It is slightly larger and heavier than its predecessor, but its wider magnet gap, expanded FOV, and other structural changes were designed to make its positioning and use generally easier and more reliable than with the PoleStar N-10. The PoleStar iMRI system, marketed by Medtronic Surgical Navigation Technologies (Louisville, CO), costs approximately $1,000,000 to purchase and install. The specifications of the PoleStar N-10 and N-20 are summarized in Table 1.

Stereotactic accuracy

We assessed the accuracy of the integrated infrared navigational tool, as previously reported [10]. A water-covered phantom was imaged in axial and coronal planes, and the onscreen distance from the virtual probe tip from the target center was measured. Measurements were taken in the center and periphery of the images as well as on images acquired in the center and upper limit of the magnetic field. Accuracy was about 2 mm or less overall, mirroring in essence the results obtained with frameless stereotactic instruments [11,12]. Accuracy was consistent in different imaging planes and throughout the magnetic field. There was a trend for greater accuracy in the center of the images compared with the periphery, but this was not statistically significant. These results are summarized in Table 2.

Table 2
Stereotactic accuracy of the PoleStar N-10 navigational tool

Plane	Range (mm)	Mean (mm)
Axial	0.5–4.3	1.8
Coronal	0.3–4.3	2.1

Surgical experience

Technique

The PoleStar N-10 is easily powered on, and the imaging program is begun. This can be done by the surgeon or an assistant. A dedicated physician extender, such as a physician's assistant or nurse, goes a long way toward ensuring the smooth operation of this or any other iMRI system. The OR table is reversed to allow room for the magnet. To begin, the PoleStar is powered on and removed from the protective cage while the patient is placed under anesthesia and lined. After patient positioning, the system is wheeled into place and parked under the head of the OR table. The patient should be placed in such a way that the magnet poles do not collide with the head or the PRF and that

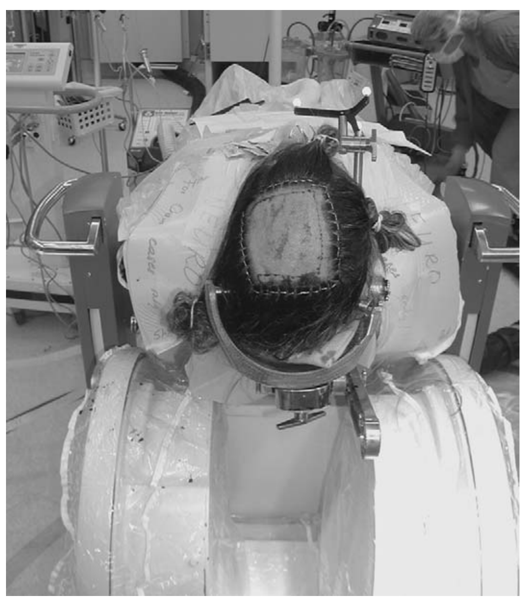

Fig. 2. Patient positioned for surgery with the PoleStar N-10.

shoulder pressure is minimized during imaging (Fig. 2). Some experience is needed to learn the nuances required to achieve this result.

With the MRF attached to the magnet and the infrared cameras positioned (typically at the foot of the table), the magnet is automatically registered. The navigation probe is placed on the scalp over the approximate area of interest; this now becomes the scan position to which the magnet can be moved. Imaging sessions should be as brief as possible and no longer than necessary. We start with an 8-second sequence labeled ‘‘esteady’’ by OMT (the generic name is a ‘‘true fast imaging steady state processing’’). This sequence combines characteristics of T1 weighting (for tissue) and T2 weighting (for fluids) and has a high signal-to-noise ratio (SNR). Adjustments to the magnet position are made as needed using these short sequences. We then acquire a 1-minute T1-weighted image without contrast, followed by a 3.5-minute image enhanced with intravenous gadolinium. This sequence, with 4-mm thick slices, usually provides excellent views of the lesion (Fig. 3). Longer scanning sequences are used on occasion for thinner slices and hence greater stereotactic accuracy, a higher SNR, or more detailed reconstructed views. We use the PoleStar mainly for surgery on patients with tumors that enhance with contrast on T1-weighted imaging, but esteady or T2-weighted sequences are preferable in some cases (eg, for a low-grade astrocytoma).

When imaging is completed, the navigation probe is placed on standard landmarks to confirm accuracy and the magnet is lowered below the table. The probe is held in one place to ensure that navigation is not affected by magnet movement (as occurs if there is relative movement between the patient’s head and the PRF). After standard preparation and draping, surgery is begun. When possible, the preoperative imaging coil is kept beneath the drapes, obviating the need for coil replacement before intraoperative scanning. Standard instruments are used, including drills, an operating microscope, and ultrasonic aspirators. The initial placement of MRI-compatible

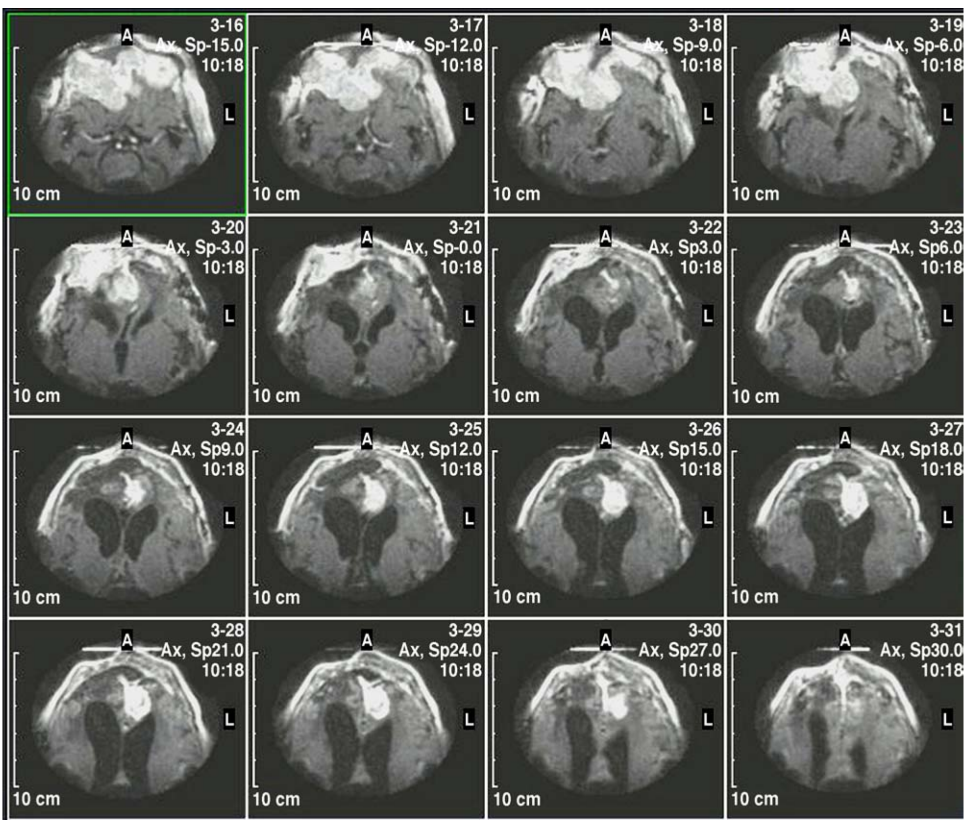

Fig. 3. Preoperative 3.5-minute image in patient with a recurrent meningioma.

retractors facilitates scanning later on. Surgery is continued until a new image is needed to rule out a residual lesion or to confirm that the surgical goals have been reached. To scan, the magnet is returned to the scan position without the need for new draping. The same imaging sequence as described previously is repeated. When appropriate, surgery can proceed with the magnet in the imaging position and successive scans can be performed (eg, for glioma resection; see case illustration of patient 1). Surgery is completed with the magnet lowered, and a final scan is obtained before the patient is awakened from anesthesia.

Patient data

Most surgery in the PoleStar N-10 was done for patients with intracranial tumors but not exclusively. These data are summarized in Table 3.

iMRI could not be obtained in 6 patients because of equipment failure. In 3 patients, planned iMRI was aborted because the patient's large body habitus made imaging in the PoleStar N-10 impossible. Neither problem has been noted to date after surgery on 12 patients in the PoleStar N-20.

Effect on surgery

In 61 of 184 patients undergoing surgery with the PoleStar N-10, iMRI revealed an additional lesion that warranted resection. Diagnoses in these cases were mainly glioma, pituitary adenoma, and skull base meningioma. In 24 patients, imaging demonstrated that the surgical goals had been reached and therefore prevented unnecessary and potentially harmful dissection from being performed. Diagnoses were similar in these patients, although the most common lesion was pituitary adenoma.

Table 3
Patient data: iMRI experience with the PoleStar N-10

Diagnoses			No.
Tumor			153
Seizures			9
Inflammatory			12
Hematoma			3
Cavernoma			1
Hydrocephalus			3
Infarction			1
Cerebrospinal fluid leak			2
Total			184
Procedure	No.	Position	No.
Craniotomy	118	Supine	157
Transsphenoidal	43	Prone	11
Biopsy and other	20	Lateral	13
Additional time (h)		No. scans	
Range 0.25–4.0		Range 1–9	
Mean 1.4		Mean 3.1	
First 10 procedures 2.6			
Last 50 procedures 1.1			

Case illustrations

Patient 1

A 28-year-old man complained of headaches. He was grossly neurologically intact, but neuropsychologic testing revealed significant cognitive deficits. dMRI revealed a nonenhancing mass growing from the left centrum semiovale to the left lateral ventricle, and this was demonstrated on the preoperative image in the OR (Fig. 4A). A left frontal transcortical approach was made, with bipolar stimulation to identify and avoid the primary motor cortex and corticospinal tract. After initial resection, with the frozen section consistent with oligodendroglioma and intraoperative imaging showing residual tumor (see Fig. 4B), microsurgical removal was continued with the magnet raised (see Fig. 4C). The "Compare" function shows progressive resection over time, from left to right, until gross imaging removal was achieved (see Fig. 4D). The patient was neurologically intact after surgery.

Patient 2

This 64-year-old woman had undergone two previous craniotomies for craniopharyngioma 14 and 10 years earlier. She now presented with an inferior visual field deficit, and dMRI showed a recurrent retrosuprachiasmatic cyst (Fig. 5A). Now, with iMRI guidance, a right coronal burr hole was made. Using a skull-mounted Navigus guide (Image-Guided Neurologics, Melbourne, FL), the navigational probe was used to plan a trajectory and distance to the cyst. A catheter was passed, and 6 mL of murky fluid was aspirated. The catheter was left in place and secured to a reservoir. iMRI showed the cyst before and after drainage and confirmed catheter placement (see Fig. 5B).

Patient 3

A 25-year-old man with intractable seizures was found to have an enhancing right temporal mass. The PoleStar N-20 was positioned for

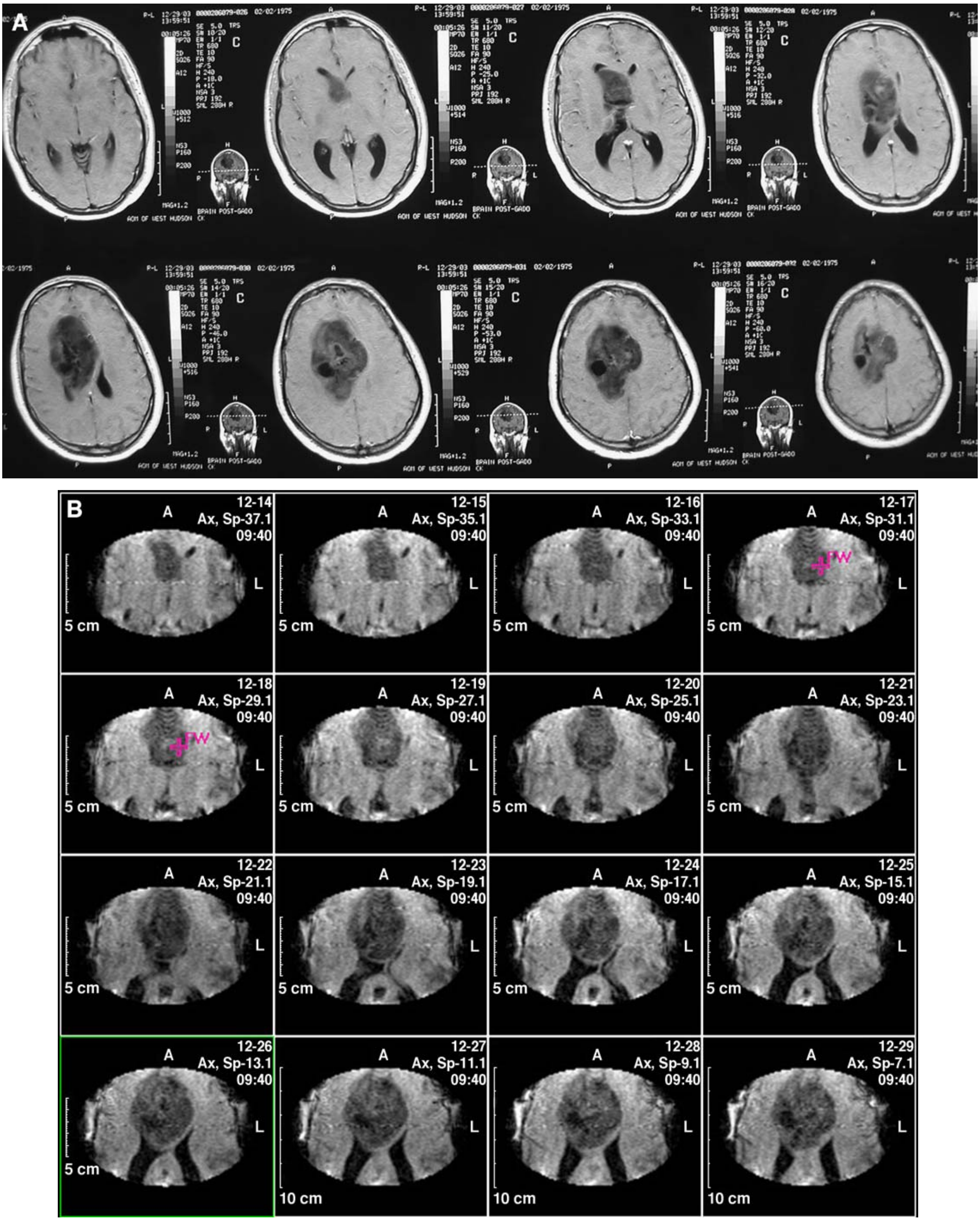

Fig. 4. (*A*) Diagnostic MRI in 28-year-old man with headache. (*B*) Preoperative image obtained with the PoleStar N-10. (*C*) Operating with the microscope through the magnet poles. (*D*) Compare function shows progressive removal at the midlevel of the tumor from left to right.

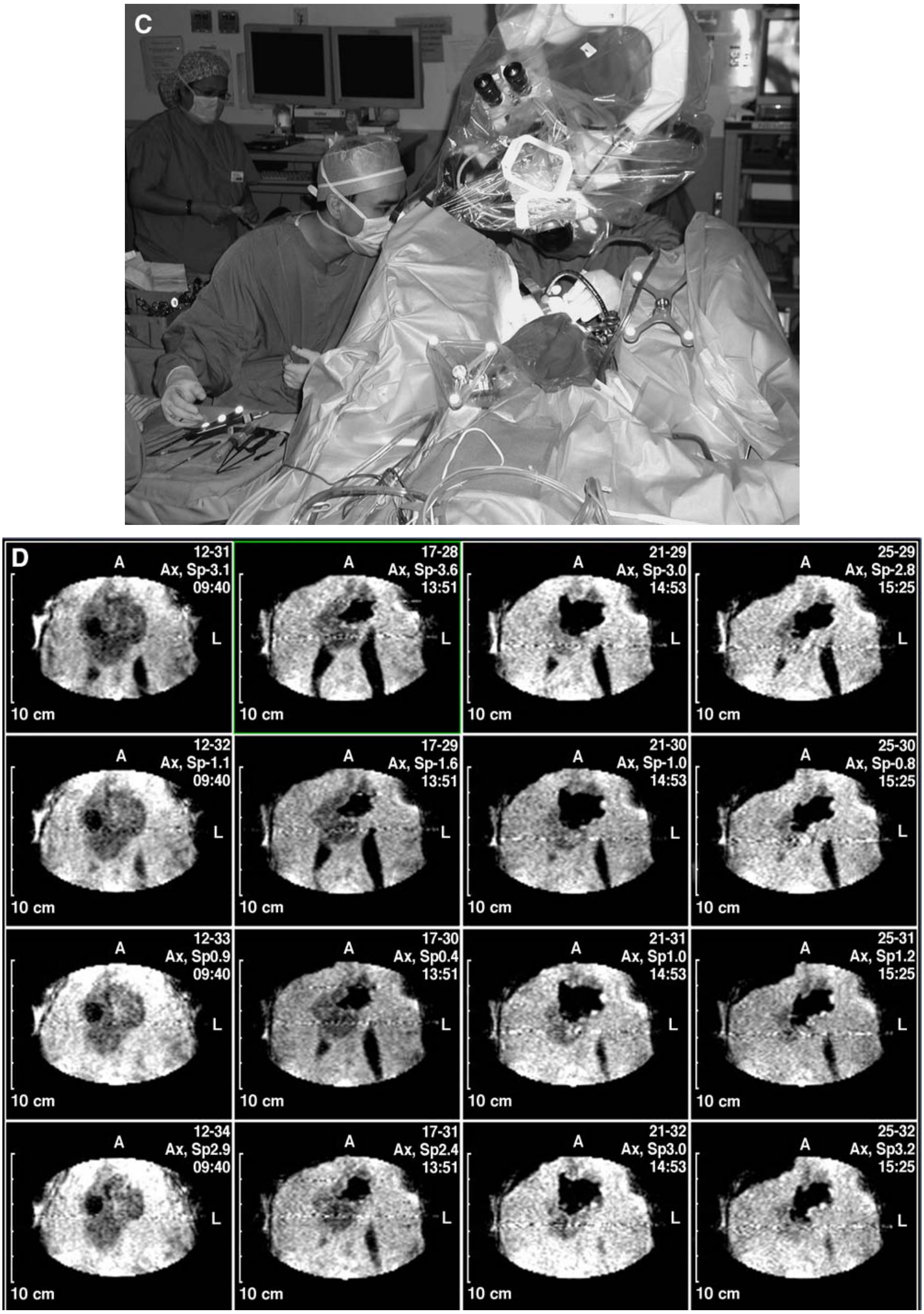

Fig. 4 (*continued*)

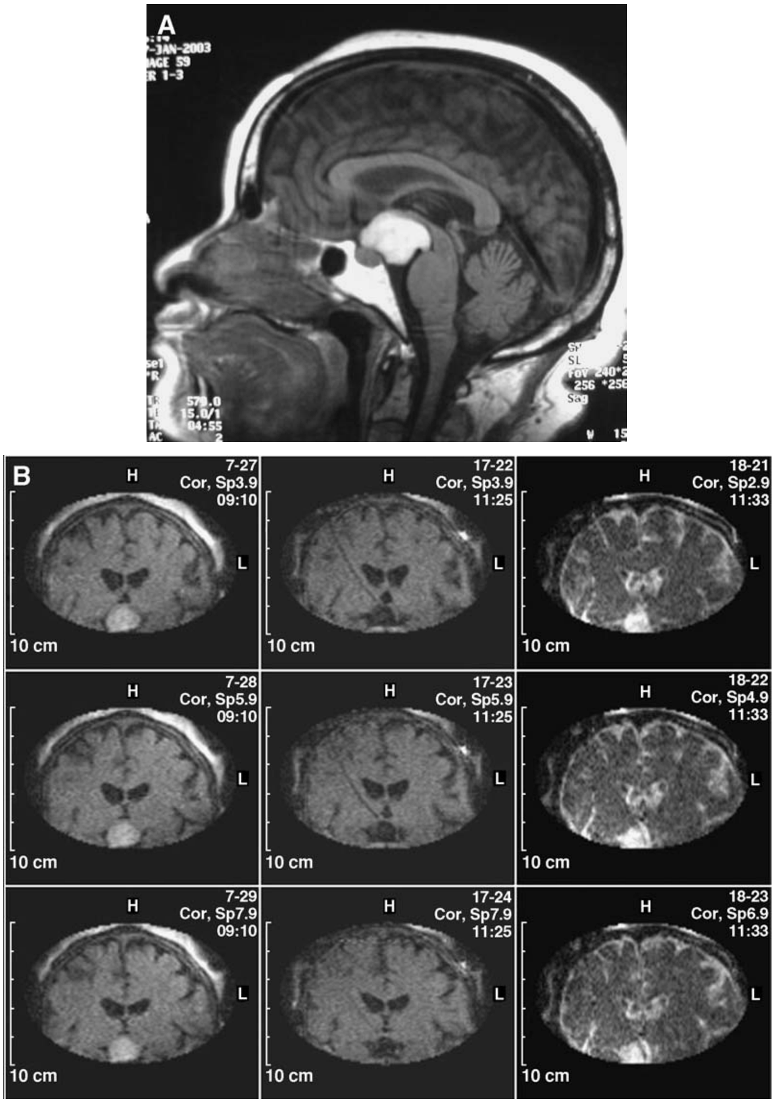

Fig. 5. (*A*) Diagnostic MRI showing recurrent craniopharyngioma cyst. (*B*) Compare display demonstrates cyst on T1-weighted coronal images before (*left*) and after (*center*) drainage; esteady scan (*right*) shows catheter in place.

surgery, and a preoperative image was obtained (Fig. 6A, B). The patient's large body habitus would have made imaging in the PoleStar N-10 impossible. After resection, the Compare function demonstrated no further enhancement (see Fig. 6C). Pathologic examination revealed a pilocytic astrocytoma.

Discussion

Is brain imaging in the OR necessary? It is fair to say that it is not required for the preoperative image, because any patient coming for elective surgery will have had such a study done before. Surgical navigation for the purpose of planning operative exposures and biopsy trajectory can likewise be done with images acquired, analyzed, and processed before the patient arrives in the OR [7]. This "decoupling" of imaging from surgery is, in fact, cited as an advantage of frameless stereotaxy over the frame-based approach [13]. What intraoperative imaging offers are two main advantages. First, and perhaps most dramatic, is the reduction in guesswork resulting from images

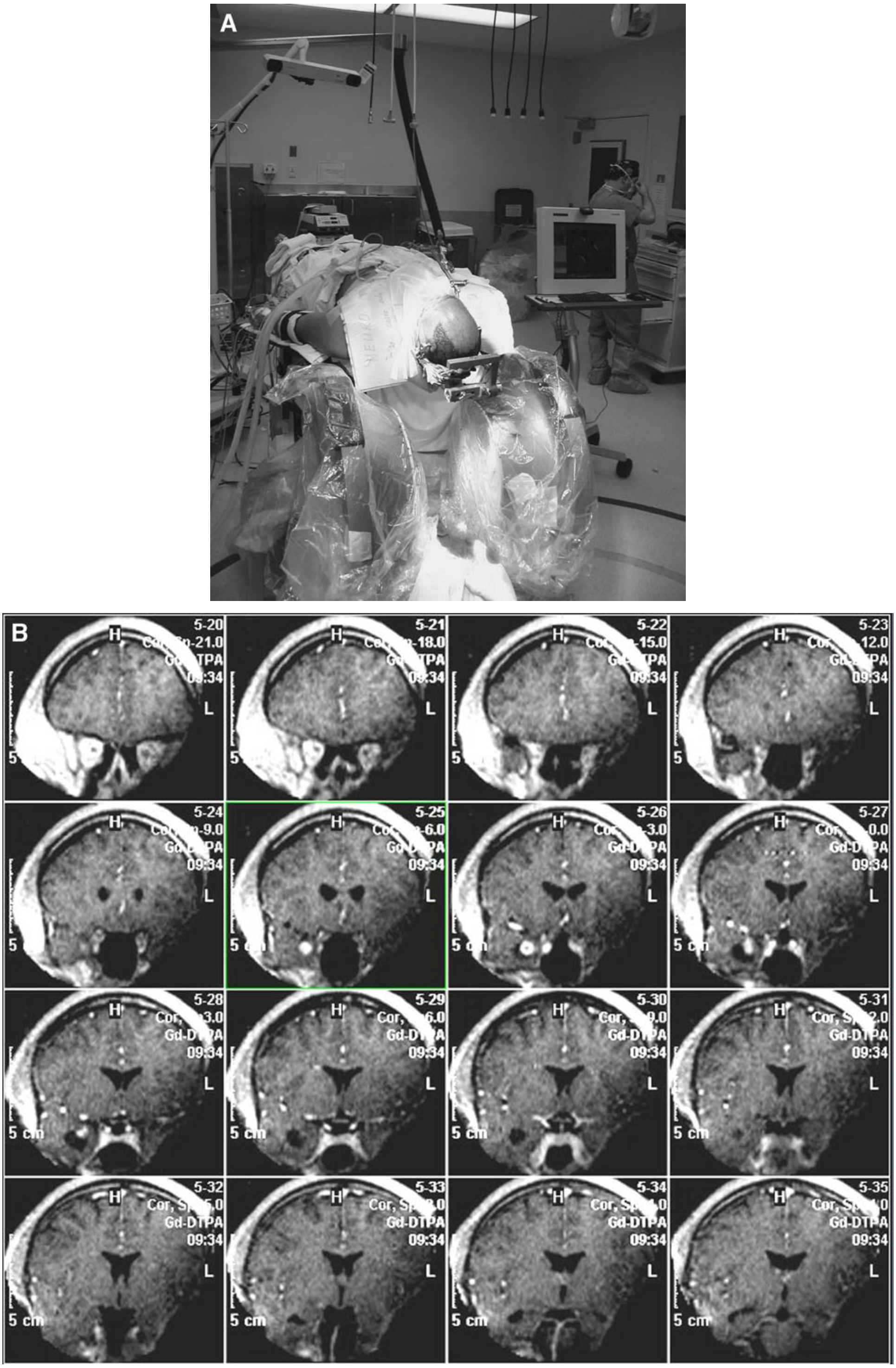

Fig. 6. (*A*) Patient positioned for right temporal surgery in the PoleStar N-20. (*B*) Preoperative coronal T1-weighted image with contrast. (*C*) Compare function before (*left*) and after (*right*) resection.

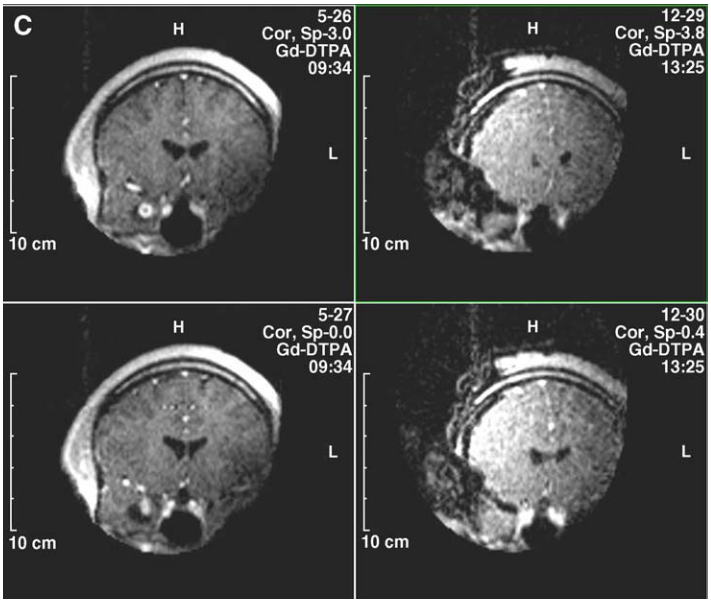

Fig. 6 (*continued*)

obtained during surgery. With the right kind of image, surgeons should no longer face surprises on postoperative scans, wishing that they had removed a large amount of residual tumor or that they had avoided the temptation to "go a little further," with consequent morbidity. After all, does any neurosurgeon who has the technology available not obtain an MRI or CT scan after surgery? How much better it would be to be able to do so during an operation. Second, by accounting for brain shift, surgical navigation can be updated rather than rendered useless or even harmful almost as soon as the dura is open [14,15].

For the foreseeable future, intraoperative imaging means iMRI. Intraoperative CT scanning, introduced 20 years ago [16] and recently refined [17], has certain advantages, including lower cost, lack of need for radiofrequency or magnetic shielding, and speed of image acquisition. It does involve the use of ionizing radiation and, perhaps more importantly, does not provide the soft tissue contrast needed for much brain imaging. Ultrasonography has been used in the neurosurgical OR and continues to be developed [18,19] but is unlikely to approach the imaging capability of iMRI. It does have the advantages of lower cost and easier integration into the OR, however.

So what kind of iMRI is necessary? As noted in the introductory section, various systems have been described and made commercially available. These have been categorized by magnet field strength [10] or by the ergonomics of patient versus magnet movement [20]. A more practical approach may to be ask how much iMRI we need. Is the ideal unit one that provides all the functions of dMRI or one that is the easiest to implement in a variety of ways? There are only so many patients with low-grade gliomas or pituitary adenomas, the indications often cited (for good reason) as being best served by iMRI. It is not possible to define a new standard for intracranial surgery for a relatively infrequent indication, nor can the issue of cost be completely ignored. Although some studies have shown early results suggesting the cost-efficiency of iMRI [9,21], much more work needs to be done in this area.

Innovative and exciting investigation of iMRI applications continues to be done at certain centers, where "full function" iMRI systems have been implemented [22–24]. These units provide not only images that are of diagnostic quality, or nearly so, but the possibility of "advanced" techniques, such as diffusion tensor imaging, functional MRI, or magnetic resonance angiography. In addition to their high capital costs, however, these units may require special personnel for their operation, mandate the surgeon to move out of the familiar OR environment, or have constraints on patient positioning—all for progressively fewer returns on increasing investment and effort. We would suggest that iMRI will become a routine part of the neurosurgical OR only when many, if not most, neurosurgeons can use it as they would any other ''high tech'' instrument, such as an operating microscope or ''conventional'' surgical navigation system. At present, and we expect in the future, it is low magnetic field strength systems that provide this unique combination of usable information and ease of use. We have shown as well that advanced applications may be possible at a low magnetic field strength, with the demonstration of motor functional MRI acquired in the PoleStar N-10 [25].

The data and images provided in this article demonstrate that for most patients who need elective intracranial surgery, and for most neurosurgeons, iMRI with a low field strength magnet and integrated navigation is an excellent adjunct that more than meets the requirements for intraoperative imaging.

Summary

Low magnetic field strength MRI provides the anatomic information needed for intracranial procedures in which intraoperative imaging is needed. Stereotactic accuracy is proven. The distinct advantage of this technologic approach is that it allows the neurosurgical team to operate an iMRI system with minimal disruption to the OR routine. Technical improvements are likely to increase the power and versatility of low field strength iMRI. Logic dictates that ergonomics and economics will make this the iMRI technique desired by most neurosurgeons.

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