Intraoperative Portable 0.12-Tesla MRI in Pediatric Neurosurgery

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Abstract

Objectives: Intraoperative MRI (iMRI) is used mainly in the adult neurosurgical population. The main indications for iMRI usage are resection control and updated intraoperative navigation capabilities. In this paper we present our experience using this technique in children. Specific advantages of iMRI for this age group are discussed.

Methods and Results: We retrospectively reviewed 31 pediatric neurosurgical procedures in which a portable iMRI system was used. The indications for iMRI usage were preoperative navigation, resection control during tumor removal, shunt placements, and needle biopsy. In 7 children the use of the iMRI changed the course of the surgical procedure. Operative morbidity and mortality were not increased with use of the iMRI. Conclusions: iMRI systems have advantages for the pediatric neurosurgical population, including both real-time basic navigation and improved resection control.

Introduction

Intraoperative MRI (iMRI) systems have been used for various neurosurgical procedures for about 10 years, mainly for adults. The benefits of iMRI in tumor resection control and in orientation during surgery for multicystic hydrocephalus have been previously documented [1–6]. The major advantage of iMRI over conventional surgical navigational systems is the ability to provide an updated data set for real-time navigation.

The low field 0.12-tesla iMRI portable system (PoleStar N-10, Odin Medical Technologies, Yokneam, Israel; distributed by Medtronic, Louisville, Colo., USA) has been previously described in several papers focusing mainly on adult pathology [1–3, 5]. iMRI may also have applications specific to pediatric neurosurgical issues [7]. This paper reviews our experience using the 0.12-tesla iMRI system for various neurosurgical procedures in pediatric patients. The discussion will include points of interest specific to the usage of this technology in children.

Materials and Methods

The PoleStar N-10 iMRI Imaging System

An extensive description of the PoleStar N-10 iMRI imaging system has been published previously [1–3, 5]. Briefly, the PoleStar N-10 system is a 0.12-tesla, low-field open MR imager with the 5-Gs line located 1.5 m from the magnet isocenter. (Five Gauss and below are considered ‘safe’ levels of static magnetic field exposure.
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for the general public. The magnetic isocenter is the point in the center of the magnet where the coordinates \((x, y, z) = 0, 0, 0\), having magnetic field strength \(B_0\) and resonance frequency \(V_0\). The critical design element of this iMRI imager is a pair of parallel, vertically oriented, permanent ceramic magnets that are spaced 23.5 cm apart. (A permanent magnet is a magnet whose magnetic field originates from permanently ferromagnetic materials, generating a magnetic field between the two poles of the magnet).

This system generates images through a number of different protocols, including the following standard protocols: (1) \(T_1\)-weighted images with 2- to 6-mm slice thickness (1–10 min acquisition time); (2) \(T_2\)-weighted images with a 4- to 8-mm slice thickness (1–13 min acquisition time), and (3) FLAIR images with 5- to 10-mm slice thickness (4–9.5 min acquisition time).

A fourth protocol was added in 2001. It was named ‘e-steady’ sequence (a combined \(T_1\)–\(T_2\) fast sequence), which produces 3- to 8-mm slice thickness images (8 s to 5.5 min acquisition time). The e-steady sequence is of lower quality compared with \(T_1\) and \(T_2\) sequences. However, it is especially useful for verification of the scanners’ position in relation to the patients’ head.

The mobile workstation includes an MRI-compatible flat panel monitor, which displays the acquired images. The system is operated either through the keyboard and mouse, or through an infrared remote control that can be draped for sterile use during surgery. A second, wired remote control is connected to the magnet’s base and is used to move the magnet.

**System Setup**

The patient’s head is secured either in a three-pin MRI-compatible headrest (Mayfield like) or placed on an MRI-compatible pinless horseshoe headrest secured with adhesive plaster. A receiving head coil is placed on the patient’s head. For surgical fields smaller than approximately 15 cm in diameter, procedures may be performed while leaving the sterile-draped coil in place. For larger surgical fields, the internal diameter of the coil (about 20 cm) may limit the exposure. In these cases the coil is encased in a sterile bag and is placed into position only during image acquisition.

This iMRI system is based upon two parallel magnetic drums that induce the magnetic field needed for the MRI scans. These drums have a diameter of 38 cm and are placed 23.5 cm apart. The patient’s head is placed within this space (fig. 1).

The system integrates a set of neuronavigational tools. Optical ‘wand’ probes are used for pre- and intraoperative guidance. These wands are pointed tools with spherical optic reflectors. Registration is performed without head-affixed fiducials, using reference frames with similar spherical optic reflectors. One reference frame is affixed to the patient’s head holder to track any movement of the patient’s head. A second reference frame is affixed to the magnetic drum. Registration is performed using a bidirectional infrared camera that integrates the position of these two reference frames with the spatial position of the wand. Navigation can be based on either 2-D or 3-D images. Optimal positioning with respect to the ovoid field of view, (approximately 15 × 11 × 11 cm), is critical to achieve high-quality images centered on the essential pathological area as well as relevant anatomical landmarks. Relevant images are scanned preoperatively for navigational as well as baseline documentation.

The system has a high spatial accuracy, with a mean navigational error of 1.8 mm in the axial plane and 2.1 mm in the coronal plane.

**Intraoperative Imaging Acquisition**

Preoperatively, the system’s components are draped in a sterile fashion and placed under the bed, using a motorized system. The surgical field is prepped and draped as usual. Surgery is generally performed using MRI-compatible tools. Note that usage of ordinary tools is also possible due to the negligible magnetic force at the operative field when the magnetic drums are placed under the bed.

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Fig. 1. The iMRI system in position for imaging acquisition. A coil is placed on the patient’s head. An infrared camera is placed in front of the system. After imaging acquisition, the magnetic drums are lowered to below the surgical bed and surgery is resumed.
When intraoperative images are needed, all tools and retractors are removed from the surgical field, the magnets are returned to their original preoperative position, and the sterile-draped coil is put into place (fig. 1). After image acquisition is completed, the magnets are retracted and placed under the bed and surgery is resumed. Typically, intraoperative acquisitions are performed either after resection of small lesions is completed, or several times at different stages during resection of large, ill-defined lesions.

**General Considerations**
System operation is generally easy, requiring only some basic training in using the software. The surgeon may operate the system alone without difficulty.

The operating room is usually shielded with copper boards, achieving a Faraday cage effect around the MRI scanner and minimizing artifactual effects. Another, slightly less expensive option is to work with mobile radiofrequency shielding [4]. This shielding enables use of the MRI scanner in a regular, unshielded operating room, thus lowering the investment costs.

**Patient Population**
Between June 2001 and June 2004, 31 neurosurgical procedures were performed using the iMRI system on 29 patients under 17 years of age (12 female, 17 male). Five children were less than 1 year, 4 between 1 and 3 years, and 20 between 3 and 17 years old.

**Pathologies**
The pathologies treated included: (1) lesion biopsies and resections (23 procedures), including 1 temporal lobectomy for treating intractable epilepsy, and (2) shunt placements (8 procedures).

Lesions (in the non-shunt cases) were found in the following locations: frontal (4), bifrontal (1), frontoparietal (3), temporal (6), parietal (2), parieto-occipital (2), occipital (2), lateral ventricles (2), and third ventricle (1).

**Scan Indications**
The indication for iMRI use was to provide a combination of real-time and updated navigational data set together with resection control in cases of lesion surgery, and verification of catheter placement in the shunted cases.

For the preoperative baseline scan an e-steady protocol for quick localization was utilized, followed by T<sub>1</sub> (without and with gadolinium) and T<sub>2</sub> studies.

The first postresection scan was performed either after the surgeon felt that the entire lesion had been removed, or when the surgeon felt the need for real-time navigational aid for orientation during surgery.

**Skull Fixation**
Pins were the standard means of skull fixation used with most of the older children. A pinless head holder with adhesive tape was used for all children younger than 3 years old and for short procedures that usually required supine positioning. No navigational or other technical difficulties were encountered in the pinless group.

**Positioning**
Most patients were positioned supine with the head turned to the relevant side. To achieve a 3/4 prone position, patients were placed on their side with the head turned. Three patients were positioned prone. Use of the iMRI did not affect the surgeon’s choice for preferred patient positioning. However, mild adaptations in head flexion extension or head rotation were occasionally required to enable comfortable and safe placement within the inter-drum space of 23.5 cm.

**Results**

**iMRI Findings**

**Tumor and Lesion Group**
Eighteen tumor and 2 cavernoma resections were performed. Preoperative images defined lesion interfaces with the surrounding brain.

In 5 cases, gross total resection was seen on the first intraoperative imaging (fig. 2, 3). In another 10 cases, residual tumor was apparent in the intraoperative imaging. In 8 of these 10 patients there was a discrepancy between the surgeon’s judgment of the amount of tumor resected and the findings on the subsequent intraoperative images. These discrepancies consisted either of an image exhibiting residual tumor, in cases where a total resection had been expected, or of an image exhibiting significantly larger residual tumor, in cases where only minimal residual was expected.

The iMRI findings were confirmed either intraoperatively or by conventional MRI following the surgery. Of the 10 patients with residual tumor, the surgeon continued with the resection and successfully removed all residual tumor in 5 cases, as demonstrated by a subsequent set of iMRI images (fig. 4). In another 3 patients, the residual tumor was deliberately not resected due to involvement of eloquent brain tissue. In 1 patient, intraoperative electrocorticography (ECOG) was performed due to the presence of an epileptic focus. No specific disturbances or problematic interactions between the iMRI and the ECOG were noted. In the 10th patient, after the residual tumor was removed, the subsequent iMRI image was of low quality and thus uninformative. Postsurgical conventional MRI images for this patient demonstrated complete resection.

Despite high-quality preoperative iMRI images, in 5 cases of the original 20 resections, the intraoperative images were of low quality and uninformative. The low quality was attributed to unidentified electromagnetic field disturbances in the operating room. In these cases, no other reason for the low quality was found, such as tumor location or positioning technique. The room setup as well as tools used were similar to other cases.

In one case the surgeon intended to use an endoscope to perform an endoscopic third ventriculostomy after resecting an intraventricular tumor. The iMRI system caused distortion of the image produced by the endoscope.
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and prevented its use. The ventriculostomy was ultimately completed under the microscope.

**iMRI-Guided Biopsy**

One biopsy (tuberculoma) was performed. The iMRI images were used for navigational purposes, verification of the location of the performed biopsy, and for postoperative reassurance that a hematoma was not present.

**Shunt Placement**

Eight shunt placements were performed. In one case the shunt was placed in a slit ventricular system, and in a second case the shunt was placed in an irregularly con-
figured ventricle. For these 2 cases the iMRI was used for primary navigational reasons only, for planning the insertion trajectory. In these 2 cases, the shunt was placed using a passive catheter stylet (PCI, PN9730092, Medtronic) under direct navigation. These procedures were meant to be short, with minimal intraoperative scans, to reduce the procedure length and decrease the risk of infection.

In the other 6 cases, shunts were placed in multicystic cavities (5 cases of multicystic hydrocephalus and 1 case of a multicystic tumor).

In all 8 cases, baseline iMRI scans were performed after positioning, before the skin incision was made. This initial scan was utilized for choosing the optimal entry point and initial trajectory, as well as for navigation within the cystic cavity. Subsequent scans were performed in 4 patients after endoscopic fenestrations of the cysts. These scans offered updated navigation data sets for resuming endoscopic fenestration of the remaining cystic cavities. After connecting the cysts, a ventricular catheter was placed.

iMRI was used to assess optimal placement of shunt catheters in 7 patients (the 8th patient woke up just before the scan was performed – thus we did not perform a postoperative iMRI scan). In 2 patients the catheter was not visible on T1 and T2 sequences. After failing to see the catheters in 2 cases, we developed other techniques to enable verifying catheter placement by the iMRI. In 3 cases, a gadolinium-filled catheter was utilized. Two central line (CVP) catheters and one ventricular catheter were filled with gadolinium and closed at the distal and proximal edges to prevent gadolinium leak. These MR-visible catheters were clearly visible on T1 sequence, thus verifying optimal catheter trajectory. Following the scan, the gadolinium-filled catheters were removed and replaced with regular ventricular catheters. In another case, 2 ml of diluted gadolinium was injected through the ventricular catheter before the iMRI scan, thus confirming catheter placement and cystic communication. In the last case, an e-steady scan demonstrated satisfactory positioning of a regular catheter. In all 8 cases, the postoperative CT scans verified satisfactory catheter placement.

iMRI was successfully used for solely preoperative navigation in 2 cases – localization of an aneurysmal bone cyst, and navigation aid in a temporal lobectomy. Thus, no intra- or postoperative scans were performed in these cases.

Complications
No iMRI-related complications were noted. On the whole, using the iMRI system added to the operating room time. However, the added time was reduced with experience. After the early learning period, we found that preoperative procedures (including patient positioning and primary image acquisition) add between 30 and 45 min. Intraoperative imaging adds about 10–15 min per instance. The duration of intraoperative image acquisition changes depending on the particular requirements of a specific surgical procedure. Despite the extension of the total anesthetic and surgical time, there were no postoperative infections in this group.

Discussion
We portray here a systematic description of the use of the PoleStar N-10 low-field 0.12-tesla intraoperative portable MRI system in a pediatric population.

As reviewed by Barnett [8], the evolutionary steps in the development of iMRI systems can be categorized into three generations. The first generation iMRI is the result of a collaborative project between General Electric (GE; Milwaukee, Wisc., USA) and the Brigham and Women’s Hospital (Harvard University, Boston, Mass., USA), producing the 0.5-tesla GE Signa system. This system is situated within the operating room, and the surgical procedure is performed within its ‘double doughnut’ design [9, 10]. The second-generation iMRI utilizes one of various standard diagnostic open or closed MRI systems that have been installed in a ‘near-by’ MR imaging unit (e.g. Siemens 0.2-tesla system, Erlangen, Germany). When working with one of these systems, the patient is transferred to the imager during or at the end of the operation [11]. The third-generation iMRI systems are portable systems designed to be placed near the patient within the operating room (e.g. PoleStar N-10).

The advantages and disadvantages of the low-field 0.12-tesla PoleStar system have been described previously [1–3, 5]. The advantages include lower costs for a system that is simple to operate and also permits the use of non-MRI compatible surgical instruments. Lately, use of the PoleStar Odin system within an ordinary operating room has become possible, using mobile radiofrequency shielding [4]. The essential limitation to date of the portable system has been its comparatively small field of view (FOV) [5], which necessitates focusing the center of the FOV near the center of the lesion of interest. The second problem is due to a relatively small distance between the magnet drums (23.5 cm). The patient’s shoulders may limit movement of the magnetic drums, which have an external diameter of 38 cm. Consequently, lesions that are situated near the skull base, especially those in the...
posterior fossa, may not be clearly visible through this system [5]. Note that the PoleStar N-20 system is a new generation iMRI in which both the FOV and the distance between the drums have been increased. This new system does enable viewing lesions in the posterior fossa.

To date, the use of the 0.12-tesla iMRI system has focused on adult patients, undergoing mostly supratentorial tumor resection, transphenoidal resection of pituitary adenomas, resection of epileptic foci, and frameless stereotactic biopsy.

**Positioning in Pediatric Patients**

Some of the recognized PoleStar limitations are significantly less applicable to the pediatric population. A narrower shoulder span and greater flexibility of the neck make it possible to place the magnetic drums more caudal compared to adults [7]. Pediatric cranial dimensions are also smaller than in an adult, thus obtaining more comprehensive data from the same FOV.

Infant heads cannot be secured with pins due to their thin skulls. In our experience, the 16 children whose heads were secured with adhesive plaster in an MRI-compatible pin-less horseshoe headrest did not experience any navigational or other technical problems such as a low-quality scan.

**Benefits of iMRI for Pediatric Patients**

iMRI use provides several advantages over standard navigation systems. Some of these advantages have special significance for the pediatric patient.

iMRI use may preclude the need for extra pre- and postoperative CT or MRI scans. Often, patients are referred to operation after undergoing diagnostic MRI imaging elsewhere, thus they may need an independent preoperative imaging for navigational purposes. Unless performed just prior to the surgical procedure, this may necessitate additional sedation or even general anesthesia, especially in small children. Neuroradiologists today are also more concerned about the long-term risks of low-dose radiation, and much care is taken to minimize children’s exposure to CT scans [12–14]. To date, no long-term consequences of short exposures to low-dose magnetic fields are known [15]. Thus the advantage of performing the navigational imaging as an MRI within the operating room, after the child has already been put to sleep for surgery, seems significant. This navigational capability may be used for many applications, such as placing a shunt in a slit or irregular configured ventricular system, optimizing surgical access to a lesion, etc. Similarly, an iMRI scan at the end of the operation may be sufficient to prevent the need for additional ‘routine’ postoperative CT or MRI scans. Thus, the iMRI may reduce the need for pre- and postoperative brain imaging scans. Still, the Odin iMRI system does not provide high-quality scans. It is therefore not suitable for replacing conventional diagnostic MRI as a tool for preoperative surgical decisions.

Another specific benefit of iMRI in children is apparent when used during surgery for multicystic lesions and multicompartmental hydrocephalus. iMRI enhances navigational accuracy during the initial surgical approach, and even more importantly facilitates accurate navigation after the cysts have been fenestrated, opened, and collapsed. This enables continuous endoscopic cystic connection in a safe manner by a staged procedure, interrupted only by updating navigational data sets with the iMRI system. Our experience in 6 cases treated for multicompartmental hydrocephalus (4 of which were operated with the aid of a neuroendoscope) was encouraging.

Several problematic issues still exist. The first is the suboptimal ability to visualize the ventricular catheter in the iMRI. This was and could further be improved by using gadolinium-filled MR-visible catheters. A second problem is distortion of the neuroendoscopic picture and color offset. These technical issues necessitate additional technical advances.

One of the most significant benefits of iMRI in children is resection control. In our group of tumor resections, 8 cases displayed a significant discrepancy between the surgeon’s impression of the amount of tumor resected and the actual residual tumor, as demonstrated by the intraoperative scans. This discrepancy changed the operative course in 7 of these patients. The iMRI enables intraoperative scans at each stage of a resection, thus providing the surgeon with a real-time perspective of the surgical field, facilitating step-by-step concentration on specific areas of the surgical bed and making it possible to attain a finer, more accurate resection. This control is especially important when working on tumors situated within or near eloquent brain tissue. Resection control is especially important in the pediatric population — in which the majority of cranial tumors are low grade and complete resection has been correlated with an improved prognosis [16, 17].

**Convenience of the iMRI System**

Most of the technical difficulties encountered with the iMRI system were manageable. Technical issues were generally resolved as part of the learning curve within the first year of usage.

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As described elsewhere [1, 2, 5], the PoleStar iMRI system functions well with routine surgical techniques and instrumentation, and no meaningful magnetic forces act on the routine surgical tools or needles when the magnetic drums are beneath the surgical bed. In our study population we used ordinary surgical tools. We also performed ECOG with no technical difficulties. We experienced some specific instrumentation incompatibility, including distortion of endoscopic pictures and intermittent malfunction of the ultrasonic aspirator. However, we found that placing the endoscopic monitor and cables as far as possible from the magnet minimized the picture distortion, thus achieving acceptable endoscopic images. Similarly, placing the aspirator system as far as possible from the magnet, as well as distant operation of the aspirator’s pedal minimized magnet-induced faults. Specific details concerning system features and installation can be found on the following website: http://www.odinmed.com/site/index.asp.

## Conclusion

iMRI potentially provides significant advantages for pediatric neurosurgery. In addition to updated resection control and real-time basic navigation capabilities, iMRI use may in some cases minimize the need for extra pre- and postoperative CT and MRI scans, thus sparing the child unnecessary radiation and general anesthesia. iMRI may also prove to be significantly beneficial in the treatment of pediatric multicystic and complicated hydrocephalus.

### References