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A low-field intraoperative MRI system for glioma surgery: is it worthwhile?

Dennis S. Oh, MD*, Peter M. Black, MD, PhD

Department of Neurosurgery, Brigham and Women's Hospital, Harvard Medical School, 75 Francis Street, Boston, MA 02115, USA

A decade ago, intraoperative MRI was regarded as a novelty and somewhat of a luxury. In the past few years, it has steadily moved toward becoming a standard of practice in the surgery of tumors located in critical areas of the brain. More and more neurosurgical centers are acquiring the equipment and setting up the facilities for intraoperative MRI–guided surgery. These facilities differ in several respects, including the design of the machine, the strength of the magnet, the operating room (OR) environment, and the surgical equipment required for performing surgery [1,2]. Each has its own set of advantages and disadvantages, and no single system has gained universal use yet as these systems continue to evolve. It has become clear, however, that intraoperative MRI has revolutionized the practice of neurosurgery, particularly in the management of brain tumors. It has enabled us to localize tumor margins and important neural structures precisely such that neurologic complications are avoided while ensuring maximal, if not total, tumor resection.

Intraoperative MRI has proven to be exceedingly useful in a variety of procedures. In transsphenoidal pituitary surgery, it has been shown to help localize the lesion, identify important surrounding structures, and, most notably, increase the amount of tumor removed [3]. The ability to verify whether there is residual tumor during surgery and to determine where it is in the resection cavity has been crucial in avoiding the common problem of residual tumor in the sella or suprasellar area. Intraoperative MRI has also been used in the evacuation of hypertensive hematomas in the basal ganglia and thalamus [4,5], with the benefit of adequate removal of hematoma in a minimally invasive fashion and observations of better neurologic outcome. Epilepsy surgery is another area in which intraoperative MRI has made a difference [6–8]. Temporal lobe resection is made more accurate in terms of removing the epileptogenic focus while maintaining the integrity of uninvolved brain tissue. Other areas of neurosurgery that have been elevated by intraoperative MRI include cyst aspiration, catheterization, and tumor resection in children [9,10]; laminectomies; thermal ablations; and functional neurosurgery [11].

Although the applications of intraoperative MRI continue to expand, its most important role is in glioma surgery. The difference it makes in achieving surgical goals for glioma patients, particularly those with low-grade types, has driven the development and growing use of intraoperative MRI.

Challenges in cortical surgery and rationale for intraoperative imaging

Inability of the eye to discern tumor

There are several reasons why intraoperative MRI is extremely helpful in glioma surgery. Many of these tumors do not have distinct capsules. As a result, the human eye is unable to discern where tumor ends and viable brain begins. This holds true even with the aid of magnification. Such a problem leads to inadequate resection of the

* Corresponding author.
E-mail address: dennis.oh@tch.harvard.edu (D.S. Oh).

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tumor, because surgeons, not wanting to cause neural damage, tend to keep the resection to what is clearly gross glioma tissue. Conversely, it may also be that without clear margins, the process of resection could inadvertently cross over to functioning brain tissue, thereby causing undue neurologic damage. There are some gliomas that are radiographically evident but barely discernible in the surgical field. For all these concerns, intraoperative MRI has proven to be the best answer thus far.

By using instant feedback from intraoperative images, one is able to tell exactly what is brain and what is tumor. Coupled with neuronavigational software, the surgeon is made aware of where his or her instrument is in the surgical space. As a result, any minute piece of residual tumor in the most obscure corner of the resection cavity can be easily pinpointed by the surgeon and removed even when his or her own eyes tell him or her that it is all brain along the walls of the surgical cavity. Some tumors do not appear on T1-weighted images but show up nicely on T2-weighted or fluid-attenuated inversion recovery images. It is thus important to use all available sequences to define the tumor.

Brain shift

One of the most important neuronavigational issues that intraoperative MRI addresses is the occurrence of brain shift. It is common knowledge that after the dura is opened, factors, such as egress of cerebrospinal fluid, gravity, and brain edema, change the position of intracranial structures [12]. The shifting occurs throughout surgery, and the direction and magnitude of deformation are difficult to predict. The displacements have been documented to reach 1 cm [13,14] and can easily lead to directional errors. Such intracranial shifting becomes even more pronounced after initial tumor resection, when the surrounding brain collapses toward the resection cavity. It is for these reasons that other neuronavigational systems that make use of preoperatively acquired images fall short of the objectives of precise lesion localization.

Brain shifting also creates tremendous problems for locating small pockets of residual tumor after initial resection. Without intraoperative updating of images, one cannot even tell whether there is still tumor remaining in the resection area. Correlating points in the resection walls to images in a frameless stereotactic system cannot accurately determine complete resection even if the limits of the resection cavity seem to correspond to the borders of the tumor in the preoperatively acquired images. With intraoperative MRI, residual tumor is readily visualized and can be easily targeted with a coupled neuronavigational system.

Relation to important cortex

The surgical challenge is doubled when the tumor is located near eloquent cortex. Oftentimes, gliomas arise near the speech area or adjacent to the motor strip, making it difficult to be aggressive in taking out tumor. Being intrinsic tumors, gliomas are intimately related to surrounding brain tissue, and their borders are frequently irregular and tend to blend into brain. In such situations, information and feedback on the surgical field are essential for complete resection without injury to important cortex.

The identification of speech, motor, or visual areas can be facilitated by functional MRI, diffusion tensor imaging (Fig. 1) [15,16], and awake cortical mapping. Information from these modalities can be combined and superimposed on the intraoperative images and the surgical field for precise and comprehensive neuronavigation (see Fig. 1). This setup helps to reduce unnecessary hesitancy on the part of the surgeon by eliminating the guesswork that is otherwise involved in determining tumor edges and the continually shifting brain structures. It may not always be possible to achieve complete tumor removal, but

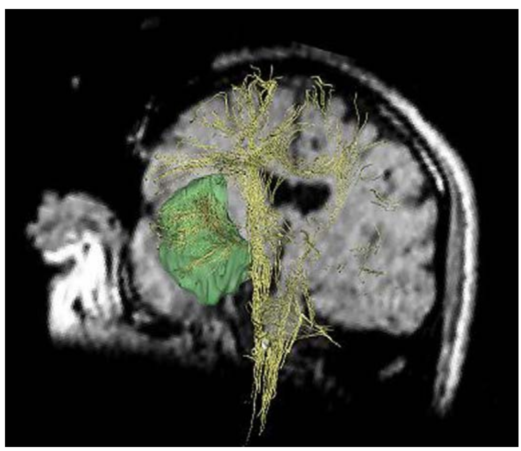

Fig. 1. Intraoperative image showing tumor (green) with added information on white matter tracts (yellow) derived from diffusion tensor imaging. (Courtesy of Ion-Florin Talos, MD, Boston, MA.)

Fig. 2. Surgeon in magnet bore. 3-D slicer probe (held by surgeon) serves as a pointer for localization of tumor and structures. Overhead LCD monitor displays updated images and exact position of probe within the surgical field.

intraoperative MRI together with mapping techniques can take us to the edge of maximal resection just before it causes neurologic complications by removing all guesswork as to the location of tumor and functional cortex. The role of intraoperative MRI in defining the tumor margins and updating the positions of intracranial structures is invaluable in achieving the goals of surgery for tumors in important areas of the brain.

Extent of resection and survival

The issue of optimal resection is made paramount by the likelihood that greater resection leads to longer survival for patients with gliomas. Although there are reports that express doubt over the relation between resection and length of survival of patients [17], most agree on the recent evidence that a more thorough resection translates to longer survival time for patients with low-grade and high-grade gliomas [18–22]. With this in mind, it becomes clear that every effort must be made to maximize our ability to achieve complete tumor resection. In this regard, among all the recent advances in neurosurgery, intraoperative MRI is proving to be the most important innovation because it has enabled us to perform surgical resection to standards that are more exacting than ever.

Brigham and Women's Hospital Magnetic Resonance Therapy Unit experience with gliomas

The Magnetic Resonance Therapy (MRT) Unit at the Brigham and Women's Hospital houses General Electric's (Schenectady, New York) "double-donut" intraoperative MRI system in a dedicated OR setup. It uses a 0.5-T magnet system within which surgery is performed. The patient remains in the same position throughout surgery between the immobile magnets. This system avoids the troubles involved in moving the patient or equipment during surgery, although it does somewhat limit the space for the surgeon. The machine is coupled to a computer-based optical tracking system that allows interactive imaging and navigation through the use of a probe [23]. Overhead liquid crystal display monitors positioned atop the surgical space display the interaction between the probe and the brain image (Fig. 2). The surgical instruments are MRI-compatible.

Most cases that have been treated at this center have been gliomas. Of the 871 procedures done at the MRT Unit from June 1995 to January 2004, 618 (71%) have involved gliomas. This great proportion bespeaks the particular utility of intraoperative MRI in assisting glioma surgery. For reasons cited earlier, gliomas pose certain challenges to the surgeon that are best addressed with the use of intraoperative MRI. Indeed, a good number of these tumors were otherwise regarded

Table 1
Types of tumor in the intraoperative MRI

Tumor type	No. of cases
Astrocytoma grade 1	16 (2.6%)
Astrocytoma grade 2	104 (16.8%)
Astrocytoma grade 3	142 (23.0%)
Glioblastoma multiforme	106 (17.2%)
Oligodendroglioma	127 (20.6%)
Anaplastic oligodendroglioma	20 (3.2%)
Mixed glioma	33 (5.3%)
Anaplastic mixed glioma	22 (3.6%)
Ganglioglioma	20 (3.2%)
Oligoastrocytoma	14 (2.3%)
Anaplastic oligoastrocytoma	5 (0.8%)
Pleomorphic xanthoastrocytoma	4 (0.6%)
Ependymoma	4 (0.6%)
Central neurocytoma	1 (0.2%)
Total	618

as difficult to resect because of their location or previous incomplete resection [14]. The uneasiness, if not unwillingness, that one may otherwise have in a case if it were not done using intraoperative MRI is greatly reduced.

There were 142 cases of anaplastic astrocytoma (23.0%), the most common tumor operated on in the MRT Unit. This was followed by oligodendroglioma, which numbered 127 cases (20.6%). Glioblastoma multiforme and low-grade astrocytoma were also often encountered, with 106 cases (17.2%) and 104 cases (16.8%), respectively. The rest of the diagnoses were pilocytic astrocytoma, mixed glioma, oligoastrocytoma, ganglioglioma, pleomorphic xanthoastrocytoma, ependymoma, and central neurocytoma (Table 1). Of the 618 cases of intraoperative MRI–guided glioma surgery, there were 517 tumor resections and 101 biopsies.

The mean age of the patients who underwent surgery with intraoperative MRI was 41 years. The youngest was a 2-year-old boy with ganglioglioma, and the oldest was an 85-year-old woman with glioblastoma multiforme.

Extent of tumor resection

Several efforts have been made to quantify the added degree of resection afforded by intraoperative MRI through updated images and navigational data. Frequently, when it appeared that all the tumor had been taken out, intraoperative imaging showed residual tumor that needed additional resection (Fig. 3). Several reports indicate that additional resection on the basis of intraoperative MRI findings of residual tumor occur in 48% to 67% of cases [24–26]. Repeated imaging and subsequent resections are performed until the objectives of resection are achieved. The rate of total resection is consequently increased by greater than 20%; as a result, total resection is achieved in close to 90% of cases [6,27,28]. In situations in which complete resection is not possible without causing harm to the patient, the objective is to leave the least amount of residual tumor. Intraoperative MRI helps to bring the resection to this limit and produces a decrease in residual tumor from 32% to 4% for low-grade gliomas and from 29% to 10% for high-grade gliomas [29].

Safety and complications

Our experience has been that the surgery with intraoperative MRI is exceedingly safe and does not carry risks on top of those related to surgery in a conventional OR setting. Wirtz et al [22] reported no complications related to the imaging procedure in 242 cases. The potential complications in intraoperative MRI are similar in incidence to those in the conventional OR setting [11]. In fact, it improves our chances of avoiding postoperative hematoma complications by detecting any hematoma formation early. The reliability of intraoperative MRI in immediately detecting hemorrhagic complications has been reported [30]. In all our cases, an additional Heme sequence is performed before closing the scalp to check for any accumulation of blood in the operative site as well as elsewhere in the intracranial cavity.

As to prevention of neurologic complications, intraoperative MRI combined with cortical mapping techniques gives an unprecedented level of patient safety. In a study done at our center, 90% of patients who underwent the operation for low-grade gliomas were functionally intact after surgery [31]. The rest had temporary hemiparesis or a mild proprioceptive deficit.

Comparison with other modalities

Image-guided frameless or frame-based stereotactic systems enjoy widespread use in neurosurgery. These systems allow accurate localization of tumors and guide the surgical approach through tracking systems that employ neuronavigational software. However, their accuracy can only be as

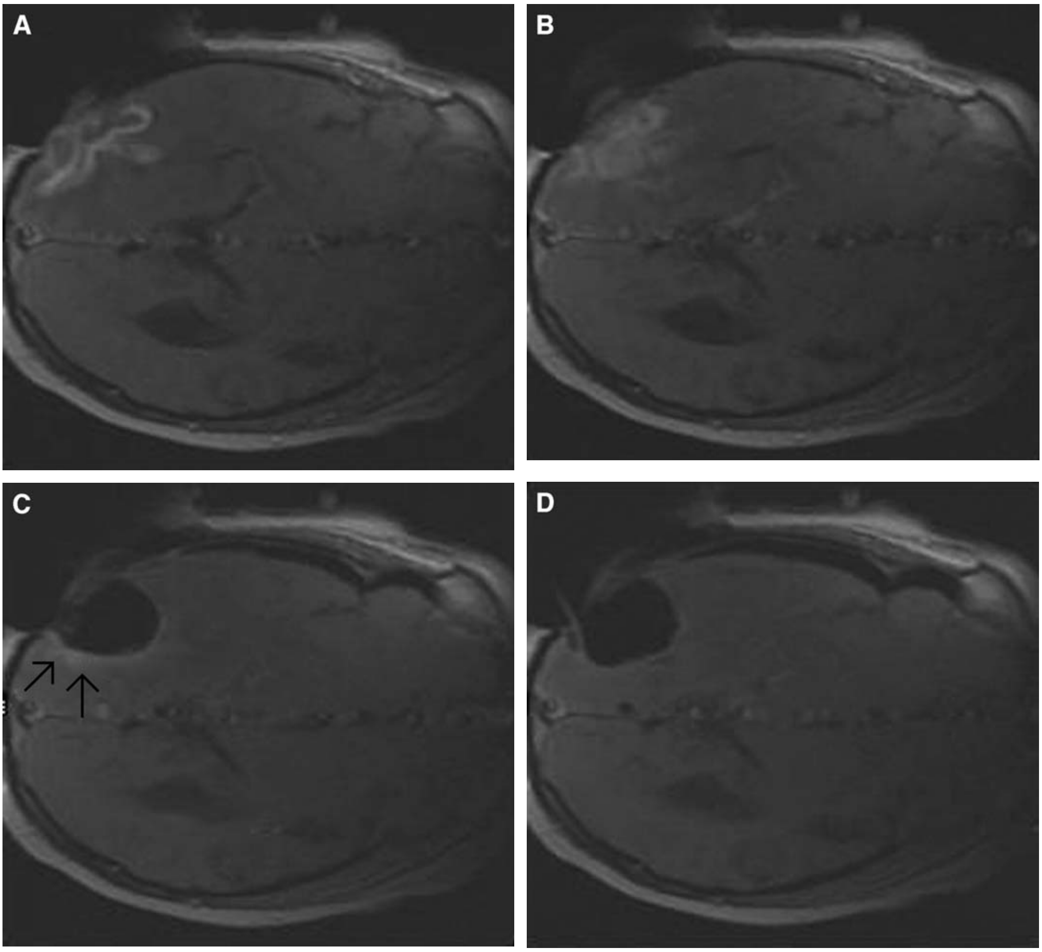

Fig. 3. (*A*) Intraoperative image of glioma before the start of resection. (*B*) Updated image after some resection. (*C*) Near-complete resection. Note residual tumor (*arrows*) that could have been missed without the aid of intraoperative MRI. (*D*) Complete resection.

good as the images on which they are based. Because the images are acquired before surgery and remain static, any change in the position of intracranial structures during surgery can affect navigational precision. Indeed, enough has been said in the literature about brain shift affecting the accuracy of such systems.

The same is not true, however, about other systems that use intraoperative ultrasonography, intraoperative CT, and x-ray fluoroscopy. They have the ability to update images during surgery and enable real-time or near–real-time navigation to obviate the concern over brain shift. They also do not require special instruments and equipment like most intraoperative MRI systems do. Each has its own set of drawbacks, however. Fluoroscopy and CT imaging are unable to provide multiplanar images, only two-dimensional images, and the image quality for soft tissues is poor. In addition, imaging can be limited by concerns over radiation exposure for the patient, surgeon, and surgical assistants. With intraoperative MRI, good-resolution multiplanar images can be easily acquired and the process can be repeated as many times as required until the goals of resection are achieved. As for ultrasonography, images are real time, easy to acquire, and good for cystic lesions. Intraoperative ultrasound is poor in delineating the borders of solid tumors, however, and is limited in its capacity to visualize small tumors. This limitation is particularly troublesome when looking for residual pieces of tumor during the course of resection. Although all these modalities currently have intrinsic limitations in their intraoperative use, there are efforts to combine their strengths to address their individual problems, such as using ultrasonographic data to update preoperatively acquired images in image-guided stereotactic systems.

Summary

As intraoperative MRI expands its presence, its use will undoubtedly increase in glioma surgery. The foregoing discussion makes it clear that its benefits are unsurpassed by any other existing system. Because of their radiographic characteristics and gross appearance, gliomas are particularly suited for intraoperative MRI–guided surgery. It enables us to localize gliomas and define tumor margins precisely when, during surgery, the difference between tumor and brain is not easy to discern. The images generated during surgery serve as a detailed and updated map within which navigation is performed with utmost precision. Its significance is further highlighted when dealing with tumors in eloquent areas of the brain, where uncertainties over the location of tumor in relation to important brain structures can hinder the removal of tumor. By providing accurate positional information and in conjunction with cortical mapping techniques, intraoperative MRI enhances the confidence of the surgeon to go forward with resection or to stop when reaching important cortex. It allows us to perform the resection to the desired limit without causing injury to nearby important structures, thereby preventing postoperative neurologic deficits.

The tracking system guides us in targeting each minute part of the tumor with unprecedented accuracy, and the ability to update images makes possible the constant evaluation of the progress of surgery. This near–real-time imaging can eliminate the errors brought about by the brain shifting that occurs throughout surgery. It also serves the important purpose of verifying the presence and position of any remaining tumor in the operative field. By means of sequential imaging, additional resection can be performed on any remaining tumor until imaging shows completion. The unwanted occurrence of finding residual tumor on a postoperative scan is thus practically eliminated. As a result, the surgical goal of complete or optimal resection can be achieved without any guesswork. Ultimately, what this means for the glioma patient is increased likelihood of longer survival brought about by a more thorough tumor resection.

Intraoperative MRI addresses many of the surgical challenges posed by gliomas. As it becomes more available, there will come a point when the prevailing persuasion will be that some poorly defined tumors near eloquent cortex should not be operated on without intraoperative MRI. In the final analysis, not only is intraoperative MRI worthwhile but it will, in all likelihood, become a standard of care for many glioma cases.

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