

The Future of Intra-operative Magnetic Resonance Imaging

a report by

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In 1993, Paul Lauterbur and Peter Mansfield were awarded the Nobel prize for their discovery that gradients in magnetic fields could be used to create images of bodily structures without harmful exposure to radiation.¹ Their work laid the foundation for the development of magnetic resonance imaging (MRI). Since their seminal work in the early 1970s, over 60 million MRI investigations have been performed using approximately 22,000 MRI scanners worldwide.¹ MRI has gained widespread use in modern medicine, particularly in the neurosciences. It is not surprising, therefore, that such technology would eventually be applied to neurosurgical operations. What follows is an overview of the current applications of intra-operative MRI (iMRI), the surgical and engineering considerations surrounding its use, and a brief discussion of the future applications for this bold new technology.

Current Applications of Intra-operative MRI

iMRI was initially described in 1993² and consists of small-scale MRI units built in MRI-compatible operative suites. The utility of iMRI lies in its ability to obtain near-realtime brain imaging during neurosurgical procedures. This is valuable for several reasons. First, the brain is susceptible to structural deformations during neurosurgical procedures. Deformations become more pronounced over the course of the operation due to brain retraction and dissection. Deformations distort anatomical landmarks and may mask the location of brain lesions. Near-realtime imaging provides the surgeon with enhanced anatomical orientation. Second, brain lesions such as tumors are frequently infiltrative and resemble the surrounding normal brain tissue. This increases the complexity of the primary goal of surgery—to maximize tumor removal while minimizing injury to normal brain. Intra-operative imaging may differentiate residual tumor from normal brain, thereby optimizing surgical resection and minimizing the morbidity associated with surgery.

Currently, iMRI is only available at a few centers. Before iMRI reaches widespread use, several conflicting considerations must be reconciled. These considerations balance the surgeon's desire to integrate an unobtrusive iMRI with the engineer's desire to integrate a scanner that produces high-quality images suitable for surgical use.

A Surgeon's Perspective

To be a useful adjunct to neurosurgical procedures, iMRI must first abide by the Hippocratic doctrine—*primum non nocere* ("first, do no harm"). Hence, the iMRI must not interfere with the neurosurgical procedure. Current limitations of iMRI are increased operative time¹ and decreased surgical access to the patient.²

Neurosurgical procedures are lengthy. Arresting the flow of an operation to obtain imaging can significantly extend the operative time. First, time is required to establish magnetic field homogeneity (i.e. shimming) and to adjust for radiofrequency (RF) effects of the local environment (i.e. tuning). The acquisition of MR images then requires various durations depending on the image sequence and the volume of interest. Beyond image acquisition, many intra-operative scanners require positioning of the scanner, or patient, within the magnetic field. Fixed-position scanners avoid this additional time, but force the surgeon to operate within the physical limits of the magnet. Sharing this confined space of approximately 50cm are the surgical assistant, operative microscope, and surgical equipment. This also constitutes a significant physical constraint on proper head position and surgical approach. Of course, all of the above must exist under sterile conditions. These considerations serve as potential obstacles to the widespread introduction of iMRI into the operating theater.

An Engineer's Perspective

There are numerous technical considerations that



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1. The 2003 Nobel Prize in Physiology or Medicine. *The Nobel Assembly at Karolinska Institute Press Release (2003)*.

2. Schenck JF, Jolesz FA, Roemer PB et al., "Superconducting open-configuration MR imaging system for image-guided therapy", *Radiology (1995);195: pp. 805–814*.

center on the engineering and design of iMRI to produce high-quality images. Image quality is directly proportional to magnetic field strength, signal to noise ratio, gradient strength, time of image capture, field of view, and RF coil features (i.e. size, geometry, quality). Magnet strength, measured in Tesla (T; units of magnetic flux density), is at the top of the list of technical considerations. While conventional clinical MRI units range from 1.5 to 3T, iMRI units are more commonly 0.3–1T. The design of the magnet itself is also critical. Several third-generation magnet designs are currently in production, including ‘double donut’ designs, suspended bore magnets and flat-bed designs. Double donut designs may be mobile or fixed. The most recent mobile version rolls up to the operative

incumbent risk of inducing intra-operative seizures. fMRI, on the other hand, could theoretically localize eloquent cortex well beyond the limits of the craniotomy without the need for electrical stimulation.

Another potential application for iMRI is that of DTI. DTI is a new technology that visualizes the axon pathways that link critical brain regions. This valuable adjunct could ‘paint’ fiber tracts so that the surgeon may confidently avoid disrupting them. Because there is no intra-operative method to demarcate these pathways, the surgeon must intuit their location by mentally accounting for anatomic landmarks and deformation. DTI would have a decided advantage over current practice.

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table. Once in position, it retracts under the table until needed. Suspended magnets, meanwhile, travel on ceiling tracks to a docking position at the head of the table. Flat-bed designs require a sliding operative table to move the patient into the magnet when imaging is necessary. Additionally, iMRI requires shielding from external RF interference. This mandates numerous adaptations to the operating suite. Routine neurosurgical instruments, such as electrocautery devices and electrophysiological monitoring equipment, are potential sources of RF interference. Finally, the operative suite itself must be shielded with lead-lined walls.

Future Applications of Intra-operative MRI

Recent technological advances in MRI, such as functional MRI (fMRI), diffusion tensor imaging (DTI), and diffusion weighted imaging (DWI), have broadened potential applications for iMRI. For example, fMRI utilizes focal changes in brain metabolism to localize eloquent cerebral functions, such as motor control, vision, and language. Currently, the surgeon must use electrical stimulation techniques to ‘map’ the exposed cortex to identify eloquent brain regions. This method is time-consuming and laborious. In the case of language mapping, it also requires a considerable amount of cooperation from an awake patient. The electrical stimulation technique carries the

A related technology, DWI, detects regions of the brain that are ischemic. Potential applications for DWI include the surgical treatment of cerebral aneurysms and arteriovenous malformations that require the placement of clips across blood vessels. Occasionally, clip placement leads to reduced blood flow in unintended brain regions. DWI using iMRI could theoretically detect ischemic regions while there is still time to adjust the clip position and prevent permanent stroke. Applications such as fMRI, DTI and DWI could reduce operative morbidity and reduce healthcare costs.

Summary

iMRI is a new technology that currently allows physicians to obtain near-realtime brain images that detect residual tumor and account for deformations during surgery. From a surgeon’s perspective, there are many hurdles that must be overcome before iMRI will be widely accepted. These include the physical constraints of the device and the requisite time to obtain MR images. From an engineer’s perspective, the operating room environment presents multiple challenges that must be overcome to reliably obtain high-quality images. If these conflicting elements are reconciled in a fiscally responsible manner, there are numerous future applications for iMRI that may reduce operative morbidity and healthcare costs while simultaneously increasing quality of life and prolonging survival. ■