The use of MRI has significantly enhanced diagnosis and measurement of response to surgical and adjuvant therapies in neurosurgery. More recently, the use of intraoperative MRI (iMRI) has expanded to assist in surgical therapy. Ultrasonography and CT are also viable options for intraoperative imaging; however, these modalities do not provide high-quality image resolution or help delineate the tumor boundary with high specificity. Furthermore, virtually all preoperative images are acquired with MRI; thus, correlation with intraoperative ultrasonography can be difficult. Other drawbacks of intraoperative CT include the use of ionizing radiation, restricted scanning plane orientation, and lack of the diverse functional capabilities that MRI can provide. Nevertheless, the overriding question remains whether the use of iMRI in neurosurgery improves clinical outcomes.

In this 2-part series, we review the current literature and address several important questions. In part I, we discuss whether iMRI increases the extent of resection in patients with brain tumors, increases survival rates, and increases the time until recurrence of cancer (commonly referred to as progression-free survival [PFS]). In part II, we address whether iMRI accurately accounts for brain shift and whether complication rates related to its use are higher, lower, or equal to those of other modalities. We also examine whether iMRI increases the time spent in the operating room or increases costs, and if so, by how much? As readers focus on these questions, they will be better able to understand the role of iMRI in clinical practice and patient outcomes.

**History**

The first “true” iMRI machine was developed at Brigham and Women’s Hospital in Boston during the late 1980s. At that time, the closed design of MRI machines prevented...
surgeons from being able to access a patient during the scanning process. From the idea that an open-concept machine would allow surgical access while maintaining imaging capabilities, multiple designs have emerged. These have branched out from the closed, tubular design to configurations such as the “double donut” made by GE and Odin, the bilplanar designs made by Siemens and others, and mobile units (Phillips and Calgary) that can be transported and adjusted. Other than design, the greatest difference in current devices is the field strength applied. There are pros and cons to both the low-field (0.12–0.5 T) and the high-field (1.5–3.0 T) systems in use today. Low-field strength is generally reported as having a lower price, but at the cost of inferior image quality. High-field strength is exactly the opposite, offering high quality but high price. Regardless of the type of system used, iMRI is quickly finding its way into the armamentarium of neurosurgeons.

iMRI and Extent of Resection

Of all the clinical factors that iMRI is helpful at evaluating, extent of resection (EOR) is where it is conclusively most beneficial. Nearly every article on the topic discusses the ability of iMRI to increase EOR dramatically, and there are many articles written specifically about the correlation between iMRI and EOR. Repeated studies show that neurosurgeons can remove brain lesions more completely using iMRI rather than the naked eye, no matter how experienced the surgeon (Table 1). For example, Chicoine et al. reported that in glioma cases, 93% of iMRI procedures achieved gross/near-total resection compared with 65% without the use of iMRI.

A small, randomized trial in Germany by Senft et al. evaluating surgery using iMRI demonstrated higher rates of gross total glioma resection and no difference in new neurologic deficits compared with surgery performed in a conventional operating room. Bergsneider et al. demonstrated similar findings in a nonrandomized cohort compared with historical controls. The largest series, which was published by Kuhn et al., concluded that iMRI achieves significantly greater tumor volume reduction in glioma surgery without higher postoperative complications.

During resection with iMRI, the surgical procedure is routinely modified to remove residual tumor on the basis of intraoperative images. Even after surgeons think they have removed the entire lesion, iMRI often shows remaining malignancy (Figure 1). Liang and Schulder reported that iMRI helps surgeons achieve maximal EOR by aiding them in visualizing the occult residual tumor. The combination of iMRI guidance with multimodal neurophysiologic monitoring allows for extended resections in glioma surgery without inducing higher rates of neurologic deficits, even when tumors are located in eloquent areas. This approach also improves patient survival and reduces morbidity.

Bergsneider et al. found that the use of iMRI improves the reliability and extent of tumor resection compared with standard image-guided frameless neuronavigation in the conventional operating room (approximately 91% resection using iMRI alone vs 79% resection using standard neuronavigation alone). Hatiboglu et al. reported that the median EOR increased from 76% to 96%, and the authors concluded that highfield iMRI is a safe and reliable technique for use during surgery to resect gliomas. iMRI is helpful in the resection of a number of tumor types in addition to gliomas. Furthermore, Senft et al. found that the rate of complete tumor resection was significantly higher in their iMRI group than in the conventional surgery group. There are more examples in the developing iMRI literature (Table 1), but the conclusion is definite: iMRI improves EOR. As this clinical application of iMRI continues to develop and be improved, the next question becomes how it will impact patient outcome.

Effect of iMRI on Patient Outcome

Although iMRI has been around for nearly 20 years, few long-term studies have attempted to determine whether...

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its use increases life expectancy and quality of life, which are perhaps the most important clinical considerations in the treatment of a patient. The results of those studies that have been performed seem to show that the use of iMRI increases survival. For example, more than 20 articles (Table 1) analyzed the effect of EOR on patient survival (assuming that iMRI increases EOR). Many support the contention that increased EOR confers a survival advantage. Claus et al. noted significantly improved survival overall relative to age-adjusted and histology-adjusted rates obtained from national databases. Similarly, Kuhnt et al. demonstrated that a high EOR and a younger patient age are associated with a significant survival advantage in patients with glioblastoma.

EOR is an important predictor of overall survival for patients undergoing recurrent surgery for glioblastoma. If gross total resection is achieved at recurrence, overall survival is maximized regardless of initial EOR, suggesting that patients with initial subtotal resection may benefit from surgery that achieves gross total resection at recurrence. Several authors, however, analyzed EOR and survival rates and demonstrated that although iMRI greatly aids in EOR, they could not state conclusively whether it provides a survival advantage to patients.

Another reason to consider maximizing EOR through the use of iMRI is that completely resecting enhancing tissue improves outcomes independently, irrespective of the histologic grade or genetic status—supporting aggressive resection. EOR is also an independent factor associated with delay of progression and malignant transformation in low-grade gliomas (LGGs). Thus, it seems that a greater EOR achieved through the use of iMRI improves outcomes in multiple parameters.

iMRI confers outcome benefits separate from those conferred by an increased EOR. For example, one study demonstrated that among patients with glioblastoma, those with perioperative complications and surgically acquired deficits are less likely to receive adjuvant therapy and consequently have worse outcomes than those who experienced no perioperative complications. Therefore, if iMRI enables differentiation of eloquent tissue, aids identification of the remaining lesion, or otherwise prevents surgical comorbidity, then it has the potential to improve postoperative outcome.

Patients with LGGs are generally considered to have among the best outcomes after tumor removal. One study demonstrated that patients with incidentally discovered (asymptomatic) lesions had better outcomes if the lesions were removed immediately rather than monitored conservatively. The study also demonstrated that surgical morbidity was lower in these patients than in those with symptomatic lesions. With such strong responses and relatively low morbidities, LGGs have the potential to respond even more optimally to use of iMRI. Use of real-time imaging during the removal of a relatively benign lesion could prove highly advantageous for patient outcome.

Although it is imperative that more research be conducted to determine the link between the use of iMRI and survival rates, preliminary data show that the application of iMRI in neurosurgery could lead to increased patient survival.
Effect of iMRI on Tumor Recurrence

For any patient undergoing cancer treatment, the hope is to eradicate the lesion. When this is not possible, as in most gliomas, the goal becomes increasing the time to recurrence of cancer. One of the ways to measure usefulness of iMRI is by comparing time to recurrence in patients who underwent resection with and without iMRI. Of 12 studies that have been reported, 10 described a longer time to recurrence with the use of iMRI. Makary et al. reported no difference in the rate of repeat resections between iMRI and conventional MRI patient groups, although time to recurrence was longer for patients whose initial resection was performed with iMRI guidance. A recent randomized controlled trial by Senft et al. to assess, among other things, the effect of iMRI on PFS demonstrated that 67% of patients in the iMRI group were stable 6 months after surgery and 33% had progressed, whereas 36% of those in the conventional group were stable and 64% had progressed (including 1 death); thus, fewer patients had progressive disease in the iMRI group than in the conventional group. These studies demonstrated that iMRI helped increase the time to tumor recurrence (principally by increasing EOR). The potential of this finding is enormous. If this technology allows increased PFS, iMRI is of tremendous benefit; however, whether increased PFS was because of a more complete resection made possible by imaging or some other factor remains to be seen.

Conclusions

iMRI is a potent tool that advances quality care for patients undergoing neurosurgical procedures. It is also evident that various obstacles must be overcome before it is fully accepted. Research shows conclusively that it is the most beneficial tool available for increasing EOR in tumor removal. Initial results also suggest that increased EOR may confer survival advantages and improve patient outcomes. In part II of this 2-part series, we review the role of iMRI in compensating for brain shift and associated perioperative complications, costs, and novel uses. As this technology continues to evolve, it will be exciting to see how it shapes the definition of quality care and patient outcomes.

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<th>Question</th>
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<tr>
<td>1. Other than design, the greatest difference in current devices is the field strength applied.</td>
<td>True or False?</td>
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<td>2. iMRI improves the reliability and extent of tumor resection compared with standard image-guided frameless neuronavigation.</td>
<td>True or False?</td>
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<td>3. In experienced hands, conventional surgery is associated with equivalent EOR as surgery performed with the use of iMRI guidance.</td>
<td>True or False?</td>
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<td>4. High-field iMRI is a safe and reliable technique to use during surgical resection of gliomas.</td>
<td>True or False?</td>
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<td>5. The combination of iMRI guidance with multimodal neurophysiologic monitoring allows for extended resection in glioma surgery without inducing higher rates of neurologic deficits, even when tumors are located in eloquent areas.</td>
<td>True or False?</td>
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<td>6. All studies to date have established a correlation between use of iMRI and PFS.</td>
<td>True or False?</td>
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<td>7. EOR is an independent factor associated with delay of progression and malignant transformation in low-grade gliomas.</td>
<td>True or False?</td>
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<td>8. Studies have demonstrated conclusively that iMRI improves EOR.</td>
<td>True or False?</td>
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<td>9. Use of iMRI seems to be associated with a longer time to recurrence after tumor resection.</td>
<td>True or False?</td>
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<tr>
<td>10. To date, use of iMRI has been limited to resection of gliomas.</td>
<td>True or False?</td>
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