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hardware and pulse sequence improvements ultimately are limited by low SNR. However, we anticipate improvement in SNR and vessel contrast enhancement with the development of high-field-strength 3-T MR imaging units. Furthermore, the approval of high-relaxivity blood-pool contrast agents will augment intravascular signal intensity and overall vessel contrast enhancement, particularly with the short TRs that are required for rapid image acquisition.

In conclusion, time-resolved contrast-enhanced MRA is emerging as means of imaging intracranial circulation with high spatial and temporal resolutions. Work must still be done to allow the acquisition of full 3D image volumes with subsecond frame rates. However, the acquisition of submillimeter isotropic volumes to depict intracranial circulation with subsecond frame rates are on the horizon.

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One of the focus sessions at the Neuroimaging Symposium: 2001 at the last ASNR meeting was entitled "Intraoperative MRI: Is It Ready for Prime Time?" The general consensus of the speakers and attendees was that the time for intraoperative MR imaging (IMRI) had indeed arrived. Now that IMRI is being performed at some 20–30 sites around the world, it has become clear that, in most cases in which neurosurgeons believe that they have achieved gross total resection, MR-visible tumor is left behind. Multiple investigators, using different systems, have validated these results since that time.

At the 1999 ASNR meeting, we presented the Long Beach Memorial data, summarizing our first year's experience with the use of IMRI to guide brain tumor resection. In 82% of the cases in which the neurosurgeons thought that they had achieved gross total resection, MR images depicted tumor that could still be resected. Although it is one thing for a radiologist to point the finger at a neurosurgeon, Peter Black, MD, Chairman of Neurosurgery at Brigham and Women's Hospital, presented essentially identical numbers at the American Association of Neurological Surgeons (AANS) meeting earlier that year. Our experience was based on results with a 0.23-T Picker/Marconi/Phillips ProView system; the much larger experience at Brigham and Women's Hospital was based on findings with the GE 0.5-T double-donut system in Dr Ferenc Jolecz's IMRI laboratory. Since that time, multiple investigators have presented and published similar results, which range from 65% to 92% with a variety of systems, including additional 0.5-T GE SP systems (Dr Thomas Kahn, University of Leipzig), a 1.5-T short-bore Philips system (Dr Chip Truwit, University of Minnesota) and a 0.2-T Siemens Open system (Dr Jonathan Lewin, Case Western Reserve, and Drs Fahlbusch and Nimsky, University of Erlangen-Nurnberg).

So the surgeons leave a little bit of tumor behind—does it really make a difference clinically? To answer this question, one needs to focus on the specific type of tumor. Clearly, high-grade gliomas that infiltrate vital structures cannot be totally resected without resultant neurologic deficits. One might argue that surgery is only palliative with such tumors, although some would point out that more complete resection of even high-grade gliomas increases the patient's longevity and improves his or her quality of life. Similarly, resection of metastatic lesions is probably also palliative because micrometastases are presumably already present. Here again, the patient's life expectancy and quality of life may be improved by resecting larger lesions that have mass effect—although few would argue that a complete cure is likely with surgical resection alone.

Cases in which gross total resection is likely to make a difference are those involving low-grade gliomas. When low-grade gliomas are completely resected, the patient is essentially cured. However, if even a small nodule of tumor is left behind, it eventually degenerates into a glioblastoma multiforme (GBM) that kills the patient. Multiple investigators have reported that the prognosis is directly proportional to the volume of tumor left behind. In the few cases in which MR imaging is performed within a few days after surgery, a finding of residual tumor usually does not result in an immediate repeat operation; the patient is usually followed up with MR imaging at regular intervals. Unfortunately, by the time the tumor remnant has begun to enlarge, it may have already degenerated into a GBM, and the opportunity for a cure will have been missed.

That tumor is left behind in such a large percentage of cases involving presumed gross total resection is understandable. Many brain tumors, particularly low-grade gliomas, have the look and feel of normal brain. Without IMRI, achieving gross total resection without being unduly aggressive is virtually impossible. With IMRI, however, the neurosurgeon can evaluate the brain at any time *during* resection, and thus, he or she can both avoid eloquent structures and achieve a more complete resection. Such imaging is generally performed with fast fluid-attenuated inversion recovery (FLAIR) and/or three-dimensional (3D) T1-weighted gradient-echo (GRE) techniques, which require approximately 5 minutes each, even with a low-field machine. Thus, IMRI has the advantages of enabling safer, less aggressive surgery and ensuring gross total resection for the price of a few minutes of imaging time. One might even make the point that an average neurosurgeon with an IMRI unit can achieve a better result than a much better neurosurgeon without such a unit. For these reasons, I have no doubt that IMRI will be increasingly used to guide neurosurgical procedures and that the number of these machines will proliferate.

Although arguing against the clinical benefits of IMRI is difficult, one might question whether it is feasible from a fiscal standpoint. Chip Truwit, MD, answered this issue in the affirmative during part of the same IMRI focus session. Because high-end operating microscopes can cost as much as $1 million, similar expenditures for IMRI machines are certainly in line with current practice. In addition, IMRI systems can be used to guide interventional radiology procedures, such as breast biopsy, to help offset the expense. At Long Beach Memorial, the technical cost of the IMRI system is easily offset by using the system to image claustrophobic and obese patients when it is not being used for neurosurgery.

The cost in physician time is somewhat greater than that in current practice, both for us and for neurosurgeons. Rather than reading images at our own convenience, we must directly interact with the neurosurgeon at specific times during the procedure. Usually, I am physically present when the preoperative IMRI examination is performed. This practice may help ensure that the correct technique is used and that the correct region is imaged. We typically use fast FLAIR and isotropic 3D GRE sequences with or without gadolinium enhancement, covering all the way to the scalp to show the contrast material–filled fiducial markers. This latter data set goes into the optical tracking system for frameless stereotaxis. My presence at this stage also helps pacify the neurosurgeon, who may be mildly annoyed about the extra time required to position the patient's head and head coil in the head holder and to obtain the MR images. This situation is less of a problem during the procedure, because most neurosurgeons believe that their increased speed as a result of improved visualization more than compensates for the extra time for intraoperative imaging. During surgery, I am present only when the images are obtained, to evaluate how the resection is proceeding. The presence of a neuroradiologist is especially important during the acquisition of the final image to ensure that all MR-visible tumor that can be resected has been resected.

Clearly, performing IMRI for brain tumor resection increases costs, both for the equipment and site and for physician time. For high-grade malignant gliomas or metastases, the additional cost may not be warranted, although perioperative morbidity rates would be expected to decrease with better intraoperative visualization. However, for low-grade gliomas, which are potentially curable with the use of IMRI, I believe that the cost can be justified.

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