because most mimics in the differential diagnosis of gliomatosis are also likely to appear as normal or low-blood-volume lesions. Indeed, the availability of relevant clinical history may be more useful in narrowing the differential diagnosis than normal rCBV values. The rCBV findings of gliomatosis are likely no more specific than those of conventional MR imaging.

Finally, the work of Yang et al begs the question: What *is* the current clinical role of rCBV imaging in brain tumor evaluation? Does it add to or compliment other functional techniques, such as PET or MR spectroscopy? One potential clinical application that may benefit from rCBV imaging is stereotactic biopsy guidance. Regions of elevated rCBV have been shown to be better correlated with high-grade malignancy than foci of enhancement on conventional MR images (3). Another potential clinical application of rCBV imaging is in the staging or subtyping of malignancy, in an attempt to predict the prognosis or response to treatment. Rather than concluding from their MR spectroscopic data that functional techniques, such as MR spectroscopy or rCBV imaging, may be a useful adjunct to conventional imaging to increase diagnostic confidence, Bendszus et al (2) conclude that "[MR spectroscopy] might be used to classify gliomatosis cerebri as a stable or progressive disease, indicating its potential therapeutic relevance." Lastly, rCBV imaging may be a useful modality for monitoring the response to treatment or early recurrence (3).

Despite widespread recent interest in the visualization of brain tumor angiogenesis, surprisingly few reports in the literature describe the rCBV imaging appearance of diverse, nonastrocytoma brain tumors, including lesions such as oligodendrogliomas. The literature about lymphomas has been contradictory, with some authors reporting low-CBV lesions and some, high-CBV lesions (the difference may depend on steroid use) (3). What are the false-negative and false-positive rates with the use of rCBV imaging for assessing brain tumor grade? After nearly a decade of research, our answers to many of these questions are still anecdotal. Clearly, this article represents a good first step–but only a first step–in more fully describing the physiologic imaging appearance of diverse, atypical, intracranial neoplasms. Much important, basic work remains to be done.

MICHAEL H. LEV, MD
Editorial Board Member
Harvard Medical School
Massachusetts General Hospital
Division of Neuroradiology
Boston, MA

References

1. Shintani S, Tsuruoka S, Shiigai T. **Serial positron emission tomography (PET) in gliomatosis cerebri treated with radiotherapy: a case report.** *J Neurol Sci* 2000;173:25–31
2. Bendszus M, Warmuth-Metz M, Klein R, et al. **MR spectroscopy in gliomatosis cerebri.** *AJNR Am J Neuroradiol* 2000;21:375–380
3. Lev MH, Rosen BR. **Clinical applications of intracranial perfusion MR imaging.** *Neuroimaging Clin N Am* 1999;9:309–331

The Emergence of Time-Resolved Contrast-Enhanced MR Imaging for Intracranial Angiography

Time-resolved contrast-enhanced MR angiography (MRA) (1), which was developed primarily for use in the diagnosis of abdominal and peripheral occlusive vascular (2), is emerging as a tool for use in the diagnosis of intracranial vascular disease. In recent years, due to advances in gradient hardware and the development of new pulse sequences, contrast-enhanced MRA can produce the high frames rates needed for intracranial applications.

In the initial intracranial application of thick-slab multiphase T1-weighted projection angiography, Wang et al (3) acquired 0.9 × 1.25-mm voxels with a thick-section (5.0-cm) two-dimensional (2D) imaging technique. They showed the feasibility of imaging the intracranial circulation with the simultaneous acquisition of two projection angles after the bolus injection of a gadolinium-based contrast agent with a rate of one frame 2.2 s. Hennig et al (4) adopted these ideas to image the pulmonary arteries with subsecond frames rates. More recently, Klisch and co-workers (5) were able to track the progress of intravascular embolization of arteriovenous malformations (AVMs) and dural arteriovenous fistulae. They obtained serial measurements of the cerebral circulation in response to endovascular treatment with a rapid 2D projection angiographic technique with an in-plane spatial resolution of 0.98 × 0.98-mm and a rate of less than one frame per second. In this issue of the *American Journal of Neuroradiology*, Coley and coworkers (6) report on the detection and classification of dural AVMs in three patients.

The use of MR techniques has several advantages compared with x-ray DSA; primarily, MR techniques are much less invasive than x-ray DSA. In addition to the fact that MR techniques produce images without the use of ionizing radiation, MR contrast agents are not nephrotoxic and have lower complication rates than those associated with x-ray contrast materials. The spatial localization possible with MR techniques also allow for the selection of a limited through-plane field of view so that targeted acquisition of the relevant vasculature is possible. Furthermore, since MR contrast agents are infused by means of a venous access site, such as that in an antecubital vein, MR angiography does not have the risk and complications associated with arterial punctures or the placement of a catheter.

Compared with nonenhanced MR imaging, such as

phase-contrast MR imaging or time-of-flight imaging, contrast-enhanced MR techniques are less susceptible to artifactual signal loss associated with the saturation of slow-flowing blood. The rapid image acquisitions that are essential for contrast-enhanced MRA reduce examination time. Typically, localizers and angiograms can be acquired in less than 15 min. Time-resolved MR images can depict complex flow patterns that may not be seen on non–time resolved MR images. This ability allows visualization of complex flow patterns or delayed arrival of contrast material through collateral vessels that form as the result of occlusions. We have seen the utility of this in the aforementioned work in the depiction of AVMs. The production of a time series of images also opens the door for innovative techniques for vessel segmentation based on temporal characteristics (5, 7). These have been shown to increase the signal-to-noise ratio (SNR) of images and allow the physician to isolate specific blood vessels from the surrounding background and venous structures.

An obvious improvement with intracranial MRA is the acquisition of three-dimensional (3D) volume images. 2D acquisitions are restricted to a few centimeters of through plane coverage by signal loss caused by intravoxel spin dephasing. In addition to the greater coverage afforded by 3D volume acquisitions, 3D images have the added benefit of SNRs higher than those of 2D acquisitions. With the acquisition of 3D volumes with isotropic spatial resolution, the radiologist has the ability to reproject the relevant features in the image for optimal display or to manually track blood vessels by using individual source images.

One means of increasing frame rates in 3D MR digital subtraction angiography (DSA) is to acquire the critical central phase-encoding values more frequently than the phase-encoding values that correspond to high spatial frequencies. This is the basis of the 3D time-resolved imaging of contrast kinetics (TRICKS) pulse sequence (1). TRICKS has been used successfully to increase the frame rate of 3D multiphase examinations by factors of 3 or 4. These rapid frame rates have been particularly useful in acquiring high-quality angiograms of the carotid bifurcation (8, 9) where rapid venous opacification has proven to be problematic. Some authors have had excellent results in acquiring 3D volumes with exceedingly high frame rates without the use of TRICKS by using partial acquisition of k-space volumes (10). However, to increase the temporal sampling rate of the imaging sequence, fewer k-space lines are acquired, and these are asymmetric about the origin of k space. These acquisitions have high SNRs, but they lack the isotropic spatial resolution required for reprojection. 2D implementation of TRICKS has been used to achieve subsecond frame rates for MR catheter tracking (11), and more recently, they have been used for intracranial multislab 2D angiography (12).

A key difference between x-ray DSA and MRA is the relation between image acquisition time and spatial resolution. In MRA, for a given field of view, the acquisition time is the product of the matrix size, number of sections and TR. This limitation forces spatial and temporal resolution to be traded off, depending on the imaging application (13). TRICKS encoding has proven to be useful in gaining three- and fourfold increases in the frame rate compared with this simple frame rate–spatial resolution relation for 3D image acquisitions. However, 3D intracranial applications require subsecond frame rates and submillimeter voxels. Therefore, time-resolved MRA of the intracranial vessels currently is limited to high–frame rate 2D acquisitions, low–frame rate 3D acquisitions, or 3D acquisitions with highly anisotropic spatial resolution.

Given the requirements of submillimeter isotropic spatial resolution with subsecond frame rates and high SNRs, much work is required to improve time-resolved MRA. The use of conventional Fourier spin-warp imaging is limited in is ability to meet the demands of intracranial MRA. However, novel approaches to MR image acquisitions are beginning to show promise in addressing some of the technical challenges in the development of conventional MRA. Radial projection reconstruction (PR) k-space trajectories were introduced as the first technique for spatial localization in MR imaging. Unlike Fourier encoding in which spatial resolution and imaging time are proportional, imaging time in radial PR acquisitions is proportional to the number of angular samples. However, unlike traditional Fourier phase encoding, in PR, decreasing the number of angular samples *does not* decrease spatial resolution. Rather, decreasing the number of radial samples results is a low-intensity streak artifact similar to those seen on CT scans. The undersampling artifact has not proven to be problematic in MR imaging, because, in contrast-enhanced MRA, blood vessels are the dominant signal source; in CT, artifact from bone can confound diagnostic findings.

Peters et al (14) have shown that undersampled PR acquisitions allows exceedingly rapid acquisition of high-spatial-resolution images with minimal artifact. In this work, they achieved factors of 4 times fast acquisitions relative to Fourier-encoded acquisition of the same spatial resolution. Vigen et al (15) combined undersampled PR with TRICKS, or PRTRICKS, encoding in the section-select direction to further increase the frame rate in high-resolution ($0.5 \times 0.76 \times 2.4$-mm voxels; rate, one frame per 2.56 s) contrast-enhanced MRA imaging of the renal arteries. The first intracranial application of undersampled PR by Barger et al (16) resulted in two- to fourfold decreases in imaging times for non–time resolved phase-contrast flow measurements in the circle of Willis. This technique recently has been extended to time-resolved, fully isotropic 3D projection acquisitions (17). Time-resolved vastly undersampled isotropic projection VIPR acquisition of $256 \times 256 \times 256$ volumes in less than 4 s is possible with an undersampling factor of 100.

An important consideration with high-spatial-resolution time-resolved acquisitions is the dependence of the SNR on the acquisition parameters. Because SNR is proportional to the voxel size and the square root of the imaging time, rapid high-spatial-resolution image acquisitions lose SNR in two ways. High-frame-rate high-resolution image acquisitions that use gradient

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.

TIMOTHY J. CARROLL, PHD
University of Wisconsin-Madison

References

1. Korosec FR, Frayne R, Grist TM, Mistretta CA. **Time-resolved contrast-enhanced 3D MR angiography**. *Magn Reson Med* 1996;36:345–351
2. Carroll TJ, Swan JS, Korosec FR, Grist TM, Mistretta CA. **Technical reliability of time-resolved CE MRA for the assessment of peripheral vascular occlusive disease.** Berkeley, Calif: ISMRM; *Proceedings of the International Society for Magnetic Resonance in Medicine:* **9th Annual Meeting Book of Abstracts.** 2001;65
3. Wang Y, Johnston DL, Breen JF, et al. **Dynamic MR digital subtraction angiography using contrast enhancement, fast data acquisition and complex subtraction.** *Magn Reson Med* 1996;36:551–556
4. Hennig J, Scheffler K, Laubenberger J, Strecker R. **Undersampled time-resolved projection angiography after bolus injection of contrast agent.** *Magn Reson Med* 1997;37:341–345
5. Klisch J, Strecker R, Hennig J, Schumacher M. **Time-resolved projection MRA: clinical application in intracranial vascular malformations.** *Neuroradiology* 2000;42:104–107
6. Coley SC, Romanowski CAJ, Hodgson TJ, Griffiths PD. **Dural arteriovenous fistulae: non-invasive diagnosis by dynamic MR digital subtraction angiography**. *AJNR Am J Neuroradiol* 2001;23:404–407
7. Bock M, Schoenberg SO, Flomer F, Schad LR. **Separation of arteries and veins in 3D MR angiography using correlation analysis.** *Magn Reson Med* **2000;43:481–487**
8. Willig DS, Turski PA, Frayne R, et al. **Contrast-enhanced 3D MR DSA of the carotid artery bifurcation: preliminary study of comparison with unenhanced 2D and 3D time-of-flight MR angiography.** *Radiology* 1998; 208:447–451
9. Carroll TJ, Korosec FR, Petermann GM, Grist TM, Turski PA. **Carotid bifurcation: evaluation of time-resolved three-dimensional MR angiography.** *Radiology* 2001;220:525–532
10. Carr J, McCarthy RM, Laub G Perles S, Finn JP. **Subsecond contrast-enhanced 3D MR angiography: a new technique for dynamic imaging of the vasculature.** Berkeley, Calif: ISMRM; *Proceedings of the International Society for Magnetic Resonance in Medicine: 9th Annual Meeting Book of Abstracts.* 2001;302
11. Unal O, Korosec FR, Frayne R, Strother CM, Mistretta CA. **A rapid 2D time-resolved variable-rate k-space sampling technique for passive catheter tracking during endovascular procedures.** *Magn Reson Med* 1998; 40:356–362
12. Strecker R, Arnold S, Schffler K, Hennig J. **Multiple slab MR Projection angiography with subsecond temporal resolution.** Berkeley, Calif: ISMRM; *Proceedings of the International Society for Magnetic Resonance in Medicine: 9th Annual Meeting Book of Abstracts.* 2001;301
13. Mistretta CA, Grist TM, Korosec FR, et al. **3D time-resolved contrast-enhanced MR DSA: advantages and tradeoffs.** *Magn Reson Med* 1998; 40:571–581
14. Peters DC, Korosec FR, Grist TM. et al. **Undersampled Projection Reconstruction Applied to MR Angiography.** *Magn Reson Med* 2000;43: 91–101
15. Vigen KK, Peters DC, Grist TM, Block WF, Mistretta CA. **Undersampled projection-reconstruction imaging for time-resolved contrast-enhanced imaging.** *Magn Reson Med* 2000;43:170–176
16. Barger AV, Peters DC, Block WF, et al. **Undersampled projection-reconstruction imaging for time-resolved contrast-enhanced imaging.** *Magn Reson Med* 2000;43:503–509
17. Block WF, Hany TF, Barger AV. **Time-resolved MRA using undersampled 3D projection imaging (VIPR).** Berkeley, Calif: ISMRM; *Proceedings of the International Society for Magnetic Resonance in Medicine: 9th Annual Meeting Book of Abstracts.* 2001;304

Achieving Gross Total Resection of Brain Tumors: Intraoperative MR Imaging Can Make a Big Difference

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