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Technical Advances and Clinical Progress in Carotid Diagnosis

Robert H. Ackerman, Morelia R. Candia and Zsolt May

resolution, two approaches can be identified. The first is to accelerate acquisition of the full space matrix with ultra-short echo and repetition (TE/TR) times that require more powerful gradient sets. The second is to restrict the size of the acquired k-space data and to use one of several methods of ''constrained reconstruction'' to generate the images in the time series. In this issue of the *American Journal of Neuroradiology* (page 263), Melhem et al have used one of the earliest and simplest of the constrained reconstruction methods, keyhole imaging. In their study, the acquisition of a complete (102 phase x 256 read) k-space reference matrix was followed by reduced acquisition of only the central 46 phase-encoding steps. While this decreased imaging time by a factor of 102/46, intrinsic spatial resolution of the update images along the phase-encoding direction would also be decreased by the same factor. With the keyhole method, the missing outer k-space rows of the update matrices are filled with the corresponding rows of the reference matrix prior to image reconstruction. Optimally, the result is a series of images with apparent high resolution.

Melhem et al observed that MIP projections generated from subtracted images had superior vessel-to-background contrast compared to MIP projections from unsubtracted images. The subtracted images, however, show only the changes between the updated and reference data sets, and thus have low spatial resolution along the phase-encoding direction (1). This limitation, with the relatively large partition thickness (5 mm), conspires to undermine the spatial resolution of their gadolinium-enhanced images, making them less impressive compared to standard TOF images. An alternative method, the so-called 3D-TRICKS (3D time-resolved imaging of contrast kinetics) proposed by Korosec and colleagues (2) produces images with slightly lower temporal resolution (4.5 sec/3D volume versus 3.6 sec/3D volume reported by Melhem et al) yet much higher spatial resolution. The 3D-TRICKS method includes intermittent acquisition of full k-space update images, shared data among update images, and temporal interpolation between acquired data sets. These capabilities improve the high spatial frequency information in the gadolinium-enhanced time series compared to the basic keyhole method.

Despite the claim by Melhem et al that their keyhole method can be implemented on clinical scanners with average gradient performance, the probability that most manufacturers will be ready and willing to do this is low. It is more likely that a sophisticated constrained reconstruction method, with minor variations among manufacturers, will become available commercially once the efficacy of gadolinium-enhanced carotid MR angiography, which can be performed by a technologist, has been demonstrated in clinical trials. Many questions remain, though. What will be the role of unenhanced TOF angiography? Which MR angiographic method will be used to examine the carotid siphon and common carotid origin for possible tandem stenosis? How well can an x-ray angiographic ''string sign'' of the cervical carotid be detected? Until these and related questions are answered, we will not know whether time-resolved, contrast-enhanced MR angiography will become the universally accepted MR method for assessing carotid disease.

BRIAN BOWEN
Member, Editorial Board
Miami, FL

References

1. Oesterle C, Hennig J. **Improvement of spatial resolution of keyhole effect images.** *Mag Reson Med* 1998;38:244–250
2. Willig DS, Turski PA, Frayne R, et al. **Contrast-enhaced 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

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In this issue of the *American Journal of Neuroradiology,* Hara et al (page 267) nicely describe a practical technique (extended field-of-view imaging [FOV]) for seamlessly integrating successive long-axis B-mode images to produce a single ''panoramic'' representation of the cervical common and internal carotid arteries, similar to that obtained with transfemoral arteriography, spiral computed tomographic arteriography (sCTA), or magnetic resonance angiography (MRA). The authors successfully examined 68 arteries in 34 patients. They found intimal thickening or luminal stenosis in 19 (28%) of 68 vessels, only two of which had a stenosis greater than 40%. In two other patients with carotid occlusion, movement artifact obviated extended-FOV imaging. In six (32%) of the 19 successfully studied vessels that had wall disease, extended-FOV imaging indicated a more topographically extensive lesion than was evident on conventional B-mode imaging. The authors conclude that the extended-FOV technique provides ''more interpretable images'' than does conventional real-time B-mode scanning, and is therefore ''clinically useful.''

Theoretically, the authors' technique may be useful for clarifying the sites of multiple lesions found during conventional B-mode imaging, for facilitating interpretation of follow-up studies of such lesions and for dissecting out the course of highly tortuous vessels. The authors did not test these hypotheses, nor do they present convincing evidence that extended-FOV imaging is clinically useful. In

sick patients applicability may be limited, considering that the technique failed in two patients with acute carotid occlusion. Its applicability in patients with advanced carotid disease cannot be assessed from this study, as only 3% of the vessels had a stenosis greater than 40%.

In vessels with widely patent lumens, identifying wall pathology (as the authors did in 17 arteries) can give potentially important information. But the clinical relevance of such observations is not yet obvious. Changes in intimal-medial thickness are the earliest manifestations of developing atheromatous disease, and progression may be modified in response to changes in lifestyle or medication (1,2), serving as a potential marker of treatment efficacy. Carotid B-mode ultrasound gives the most precise information about early changes in wall thickness. Nonetheless, without systematic epidemiologic studies that correlate clinical and sonographic findings, how to use such information remains intuitive guesswork.

Hara and his colleagues found that the extended-FOV technique missed nothing that was shown by conventional B-mode sonography but neither was anything identified that was qualitatively different. Extended-FOV imaging, which does not depict the common or internal carotid artery more caudally or cephalically, respectively, than does conventional B-mode sonography, only changed the interpretation of the topographic extent of disease in six cases. Whether in practice the "panoramic" reconstructions will critically alter interpretations of experienced neuroradiologists used to reading segmented data is debatable. With spiral CT angiography and MR angiography neuroradiologists often find that axial "raw data" images provide more definitive diagnostic information about stenosis than do the reconstructed data.

Of long-term relevance, the authors' results do not suggest that extended-FOV imaging will enhance the capability of B-mode sonography to address contemporary diagnostic or research issues in carotid-related stroke disease. B-mode imaging is an important part of the carotid ultrasound noninvasive battery, but it has not played a primary role in the diagnosis or understanding of carotid lesions that put a patient at risk for stroke. In 1977 our Neurovascular Laboratory had perhaps the first small-parts B-mode scanner in a carotid noninvasive laboratory. Despite the high (0.8–1.6-mm lateral) resolution of the prototype analog investigational unit (developed by Stanford Research Institute, Palo Alto, CA; later manufactured and marketed as Microview, by Picker), it was apparent within months that hypoechoic disease and shadowing from calcific plaques would markedly limit the diagnostic utility of B-mode imaging (Ackerman RH, presented at the 23rd annual meeting of the American Institute of Ultrasound in Medicine, San Diego, 1978).

Suggestions that B-mode imaging can help characterize stroke risk by differentiating "soft" (putatively thrombus-containing) from "hard" plaque (3–5) in our opinion needs further consideration. For example, we have recently seen an asymptomatic patient with a soft plaque that narrowed the vessel to a 1-mm residual lumen diameter (>80% stenosis). The endarterectomy specimen showed a glistening intima along the entire length of the stenosis with no evidence of ulceration or clot.

Carotid ultrasound has the potential to help us understand the role of advanced internal carotid artery stenosis in the pathophysiology of stroke. But to achieve this, future investigative efforts need to focus on how to determine: 1) precise degrees of severity; 2) plaque characteristics (including severity) that carry a high risk of stroke, and mandate consideration of intervention by surgery or stent placement; and 3) the plaque and clinical features that favor stent placement over surgery.

Despite (or because of) the North American Symptomatic Endarterectomy Trial (NASCET), the Asymptomatic Carotid Atherosclerosis Study (ACAS) and the European Carotid Surgery Trial (ECST), room remains for fresh research into how one precisely determines degree of carotid stenosis, and what severity of stenosis represents a real risk for stroke. Perhaps 85% of strokes caused by carotid artery disease occur on an embolic basis; the remainder are caused by low flow. The common denominator for both mechanisms typically is a "tight" stenosis of the internal carotid artery. What severity of stenosis may be considered "tight"— significantly predisposing one to stroke and mandating consideration of endarterectomy—remains controversial. For symptomatic patients, ECST implicates an 80% (6) and NASCET a 70% (7) stenosis (less in pending data), whereas for asymptomatic patients, ACAS points to a 60% (8) stenosis, but ECST conclusions don't justify surgery for any degree of stenosis (9). The Europeans and the North Americans measured stenosis differently in their studies, but this doesn't entirely account for the discrepancies in the results. In our Neurovascular Laboratory our observations suggest that real stroke risk begins with a residual lumen diameter of 1mm or less (approximately an 80–85% stenosis) (10,11).

As we have previously pointed out (10,11), percentage of stenosis may not be a physiologically precise parameter, as it does not relate to a uniform, absolute degree of stenosis or hemodynamic change between patients. The normal distal internal carotid artery, which represents the denominator in the percentage calculation, varies between individuals. Depending upon whether the distal (normal) internal carotid artery has a 5-, 6- or 7-mm residual lumen diameter, a 70% stenosis may represent a 1.5-, 1.8-, or 2.1-mm residual lumen diameter, respectively, representing a different stroke risk in each situation. Additionally, because the internal carotid artery narrows distal to a critical (0.5–0.7-mm residual lumen diameter) lesion, calculating the percentage of stenosis in the circumstance will lead one to underestimate the true severity of the patient's condition. For these reasons we routinely

report our ultrasound findings in terms of estimated residual lumen diameter, giving decrements of 0.25 mm when the lumen is less than 2.5 mm.

Whether measuring a precise residual lumen diameter serves a useful purpose is questionable to those individuals who believe that signal drop-out revealed by MR angiography is all that is required to identify a surgical lesion. In our opinion this criterion is imprecise. Signal drop-out may occur frequently with 65–70% stenosis (12), but has been reported also with 40–60% stenosis (12,13). Once signal drop-out occurs, no current conventional MR angiographic data can help characterize reliably the actual degree of stenosis until the distal internal carotid artery is seen to narrow compared to the opposite (more normal) side. In our experience this distal narrowing is apparent on MR angiograms when the residual lumen diameter is 0.9 mm or less (85–90% stenosis). With spiral CT angiography and transfemoral arteriography, distal constriction of the vessel occurs when the residual lumen diameter is 0.5–0.7 mm (11). MR angiography probably simulates this change earlier because of slow, unenhanced flow along the edges of the vessel. Spiral CT angiography cannot help one determine residual lumen diameter reliably because the thickness of the contrast column is dependent upon window settings, and extensive calcification can obscure the intraluminal contrast.

Carotid Doppler ultrasound gives the most precise noninvasive data on residual lumen diameter, although it can be misleading when the lesion is so tight (0.5–0.7mm, in our experience) that blood flow falls and frequencies and velocities begin to drop to lower values that ordinarily are used to characterize less severe disease. Otherwise, it can reliably differentiate, for example, between a 2-mm and 1-mm residual lumen diameter, which is important. Our clinical experience indicates that a 2-mm residual lumen diameter (65–70% stenosis) is a relatively benign lesion that can be followed, whereas a 1-mm residual lumen diameter (85–90% stenosis) represents a high risk for stroke (11). Further, our data suggest that a 2-mm residual lumen diameter does not necessarily progress to a tighter stenosis. If both these latter observations are correct, surgery on a 2-mm residual lumen diameter may be unnecessary in some patients.

In sum, major issues in carotid disease remain unsettled. If advances in carotid ultrasound imaging are to help resolve them, the new techniques need to characterize meaningful physiologic and anatomic details that elucidate ischemic mechanisms, reflect the prevalence of stroke risk factors, and anticipate clinical events. Extended-FOV permits B-mode images to mimic the "panoramic" vascular profile provided by spiral CT angiography, MR an-giography, and transfemoral arteriography. This adds convenience to the interpretative process, which might be more important for communicating findings to the referring physician than for providing diagnostic insights.

ROBERT H. ACKERMAN
Member, Editorial Board
Neurovascular Laboratory
Massachusetts General Hospital
Boston, MA

MORELIA R. CANDIA
Neurovascular Laboratory
Massachusetts General Hospital
Boston, MA

ZSOLT MAY
Neurovascular Laboratory
Massachusetts General Hospital
Boston, MA

References

1. Crouse JR III, Byington RP, Bond MG, et al. **Pravastatin, lipids, and atherosclerosis in the carotid arteries (PLAC-II).** *Am J Cardiol* 1995;75:455–459
2. de Groot E, Jukema JW, van Boven AJ, et al. **Effect of pravastatin on progression and regression of coronary atherosclerosis and vessel wall changes in carotid and femoral arteries: a report from the Regression Growth Evaluation Statin Study.** *Am J Cardiol* 1995;76:40C–46C
3. Golledge J, Cuming R, Ellis M, Davies AH, Greenhalgh RM. **Carotid plaque characteristics and presenting symptom.** *Br J Surg* 1997;84:1697–1701
4. el-Barghouti N, Nicolaides AN, Tegos T, Geroulakos G. **The relative effect of carotid plaque heterogeneity and echogenicity on ipsilateral cerebral infarction and symptoms of cerebrovascular disease.** *Int Angiol* 1996;15:300–306
5. Polak JF, Shemanski L, O'Leary DH, et al. **Hypoechoic plaque at US of the carotid artery: an independent risk factor for incident stroke in adults aged 65 years or older. Cardiovascular Health Study.** *Radiology* 1998;208:649–654
6. **Randomised trial of endarterectomy for recently symptomatic carotid stenosis: final results of the MRC European Carotid Surgery Trial.** *Lancet* 1998;351:1379–1387
7. Barnett HJM and the North American Symptomatic Carotid Endarterectomy Trial Collaborators. **Beneficial effects of carotid endarterectomy in symptomatic patients with high-grade carotid stenosis.** *N Engl J Med* 1991;325:445–453
8. Toole JF. **ACAS recommendations for carotid endarterectomy. ACAS Executive Committee.** *Lancet* 1996;347:121
9. **Risk of stroke in the distribution of an asymptomatic carotid artery. The European Carotid Surgery Trialists Collaborative Group.** *Lancet* 1995;345:209–212
10. Ackerman RH, Candia MR. **Identifying clinically relevant carotid disease (Editorial).** *Stroke* 1994;25:1–3
11. Ackerman RH. **Neurovascular non-invasive evaluation.** In: Taveras JM, Ferrucci, Jr, JT, eds. *Radiology* Philadelphia, PA: Lippincott-Raven Publishers; 1995;1–28
12. Heiserman JE, Zabramski JM, Drayer BP, Keller PJ. **Clinical significance of the flow gap in carotid magnetic resonance angiography.** *J Neurosurg* 1996;85:384–387
13. Enochs WS, Ackerman RH, Kaufman JA, Candia MR. **Gadolinium-enhanced MR angiography of the Carotid Arteries.** *J Neuroimag* (in press)