Contrast-Enhanced Magnetic Resonance Angiography of the Cervical Vessels
Experience With 422 Patients

Thanh Phan, MD; John Huston III, MD; Matthew A. Bernstein, PhD; Stephen J. Riederer, PhD; Robert D. Brown, Jr, MD

Background and Purpose—Contrast-enhanced magnetic resonance angiography (CEMRA) permits acquisition of high-spatial-resolution, venous-suppressed, 3D MR angiograms of the cervical carotid and vertebral arteries. In this study, an elliptic centric-view ordering with either MR fluoroscopic triggering or test bolus timing was used. The use of CEMRA of the cervical vessels has changed our clinical practice and is replacing conventional angiography for the evaluation of most carotid and vertebral artery diseases.

Methods—We retrospectively reviewed our experience with the use of CEMRA performed in 422 patients from January through December 1999.

Results—CEMRA was performed to evaluate transient ischemic attack and ischemic stroke in 239 patients, asymptomatic carotid bruit in 88 patients, and other neurological symptoms in 95 patients. Carotid endarterectomies were performed in 97 patients (103 procedures), and conventional angiography was performed in 12 of these patients. CEMRA was used to evaluate for the presence of an arterial dissection in 85 of the 239 patients with transient ischemic attack and ischemic stroke. Of this group, 32 patients had cervical arterial dissection, and pseudoaneurysm was detected in 11 of these patients. Compared with ultrasonography of the cervical vessels, CEMRA provided additional information in 43 of 422 patients and led to changes in the decision as to whether to perform carotid endarterectomy in 5 patients.

Conclusions—Use of CEMRA permits noninvasive evaluation of patients suspected of having carotid or vertebral disease and avoids the potential complications of conventional angiography. (Stroke. 2001;32:2282-2286.)

Key Words: cerebral ischemia ▪ cerebral vessels ▪ magnetic resonance angiography ▪ stroke ▪ stroke prevention

The North American Symptomatic Carotid Endarterectomy Trial (NASCET) and European Carotid Surgery Trial (ECST) have shown the benefit of carotid endarterectomy (CEA) for patients with symptomatic and severe carotid artery stenosis. The Asymptomatic Carotid Atherosclerosis Study (ACAS) has shown the possible benefit of CEA in asymptomatic patients with severe carotid artery stenosis.1–4 The use of conventional angiography in the presurgical evaluation of these patients before CEA can result in complications such as transient ischemic attack (TIA) and ischemic stroke in 4%, disabling ischemic stroke in 1%, and mortality in 0.1% of patients.5 Thus, a substantial portion of the risk of CEA is associated with the catheter angiographic evaluation. This risk may limit the benefit of CEA in ischemic stroke prevention, and it highlights the need to explore alternative preoperative diagnostic methods. Contrast-enhanced magnetic resonance angiography (CEMRA) offers high-spatial-resolution images that are beginning to approach the resolution of those obtained with conventional angiography in most patients without the complications associated with catheter-based angiography.6,7 In our practice, CEMRA of the extracranial vessels has replaced most conventional angiography for the evaluation of carotid and vertebral artery diseases. The purpose of this study was to review our clinical experience with CEMRA.

Subjects and Methods
We conducted a retrospective review of CEMRA examinations obtained from January through December 1999 for the evaluation of cerebrovascular diseases and other neurological symptoms. This study was performed with institutional review board approval. When both ultrasound and CEMRA were performed within 1 month, sonographic findings of the cervical vessels and CEMRA were compared. A comparison study between conventional angiography and CEMRA has been published.6 The status of the carotid artery as imaged by both ultrasonography and CEMRA was graded as normal, mild stenosis (<39% occluded), moderate stenosis (40% to 69%), severe stenosis (70% to 99%), or occluded. When imaging studies reported the grade of stenosis in different categories, the studies were reviewed and a consensus finding of the grade was determined for each imaging study. This scale is designed to facilitate comparison between the 2 imaging techniques. We also noted when CEMRA provided additional findings compared with sonography. Three-dimensional time-of-flight (3D TOF) MRA of the circle of Willis was performed in the same MR examination as CEMRA in 404 of

Received November 6, 2000; final revision received April 5, 2001; accepted June 28, 2001.

From the Departments of Diagnostic Radiology (T.P., J.H., M.A.B., S.J.R.) and Neurology (R.D.B.), Mayo Clinic, Rochester, Minn. Reprint requests to John Huston III, MD, Department of Diagnostic Radiology, Mayo Clinic, 200 First St SW, Rochester, MN 55905.

© 2001 American Heart Association, Inc.

Stroke is available at http://www.strokeaha.org

2282
the 422 patients (96%). The 3D TOF MRAs were not considered in the assessments of whether CEMRA provides additional findings compared with sonographic reports. When the original decision to perform CEA was based on the sonographic findings, we also recorded when the additional findings on CEMRA caused a change in the decision to perform CEA.

Magnetic Resonance Angiography

The MR examination was performed on a 1.5-T Echospeed Scanner (GE Medical Systems). The examination was performed with a volume neck coil (Medical Advances). It included a 2D phase-contrast (2D PC) coronal scout, followed by an axial 2D TOF series, and finally the bolus gadolinium-enhanced 3D gradient recalled echo sequence. The 2D PC scout image was obtained by use of a 22×16-cm field of view (FOV), 80-mm-thick coronal volume, and an aliasing velocity or velocity encoding of 60 cm/s. This scout view was used to establish the volume to be imaged with 2D TOF. The 2D TOF MRA was performed with 100×1.5-mm-thick axial sections, prescribed from superior to inferior, with the first section positioned just superior to the petrous portion of the internal carotid arteries as depicted on the 2D PC scout image. The 2D TOF sequence included an 80-mm-thick traveling superior saturation band for venous and lipid suppression, a repetition time of 38 ms, an echo time of 8.7 ms, number of excitations=1, a 256×128 matrix, a 50° flip angle, and a 16×16-cm FOV.

CEMRA was performed with a 20 to 22×15.4-cm FOV coronal slab, with a slab thickness of 5.3 to 6.2 cm, 38 to 44 sections that were 1.4 mm thick, a repetition time of 6.6 ms, an echo time of 1.6 ms, a flip angle of 45°, and a matrix of 256×224. Reconstruction used zero filling in all 3 directions to double the number sections with a resulting 0.7-mm thickness and to provide a 512×512 display matrix. A 20- to 25-mL bolus of gadolinium was administered by a power injector at a rate of 3 mL/s. Either fluoroscopic triggering or test bolus dose timing was used to determine the time to maximal enhancement of the arteries. The technique was developed using the fluoroscopic triggering technique that required assistance from nonclinical research personnel. As the sequence gained wide clinical use, a timing sequence was required because of the high volume of examinations. Both the fluoroscopic triggering and the test bolus techniques resulted in diagnostic exams in >98% of patients. The scan time was 44 to 52 seconds. During scanning of the cervical arteries, patients were instructed to breathe quietly and not to move. The 22-cm FOV was incorporated into the protocol early in the clinical experience. This coverage allowed imaging of the vertebral arteries from their origins to the proximal basilar artery. Most of the common carotid arteries and the internal carotid arteries to the mid siphon were also within the imaging volume. When clinically warranted, a second CEMA, of the aortic arch, was performed in 87 patients. Imaging parameters for the arch studies were a 24×24-cm FOV, 256×192 matrix with 38 to 44 sections that were 2.0 mm thick, resulting in an acquisition time of 49 to 57 seconds. Reconstruction used zero filling to double the number sections, resulting in a 1-mm thickness. During the aortic arch study, the patients were requested to suspend breathing in midbreath during the first part of the acquisition. The contrast information of the image is depicted on the 2D PC scout image. The 2D TOF sequence included just superior to the petrous portion of the internal carotid arteries as prescribed from superior to inferior, with the first section positioned in the decision to perform CEA.

Ultrasonography

Ultrasound of the cervical arteries was performed with color Doppler and duplex spectral analysis with a 5.0- or 7.5-MHz linear-array transducer. The degree of stenosis was determined by duplex spectral analysis in the area of flow disturbance or visible stenosis on color Doppler. A comparison of sonographic carotid artery stenosis with catheter angiography from our institution was previously published.9

Results

We performed CEMRA in 422 patients during the 12-month study period. Mean and median ages were 65 and 68 years, respectively, with a range of 2 to 94 years; 62% of patients were male. CEMRA was performed to evaluate TIA and ischemic stroke in 239 patients, asymptomatic carotid bruit in 88 patients, and other neurological symptoms in 95 patients. CEA was performed in 97 patients (103 CEAs), and conventional catheter angiography was done in 12 of these patients.
Vertebral Artery Disease
Atherosclerotic disease of the vertebral artery was present in 109 patients and dissection in 10 patients. Stenosis in these

CEMRA Versus Ultrasonography
Ultrasound and CEMRA were performed within 1 month of each other in 196 of the 422 patients. There were differences between sonographic and CEMRA findings in the carotid arteries for 22 patients (11%) and in the vertebral arteries for 19 (10%). Compared with ultrasonography of the cervical carotid and vertebral arteries, CEMRA provided additional information in 43 patients (22%), including identifying ulcerations or determining that the size of stenosis was different than indicated on sonography. In addition, CEMRA resulted in a change in the decision as to whether to proceed with CEA in 5 patients (3%) (Figure 1). Details concerning these patients are provided in the Table.

CEMRA After CEA
Correlation between CEMRA and conventional angiography after CEA was examined in 9 patients; carotid ultrasound was performed in 8 of them. There was agreement between CEMRA and conventional angiography in 8 of the 9 patients. In these 8 patients, the measured degrees of stenosis of the CEMRA and the conventional angiogram were within 10%, and there was no change in the category of stenosis. The discrepancy in 1 patient was due to an artifact from a surgical clip placed during a prior CEA, leading to signal loss in the left common and internal carotid arteries (Figure 2). On CEMRA, the clip gave the false appearance of luminal irregularity and severe stenosis in the left common and internal carotid arteries. In the other patients who had patch grafts during endarterectomy, there was no noticeable artifact on CEMRA.

Disagreement between CEMRA and ultrasound was present in 2 of 8 patients. In 1 of these patients, ultrasound correctly identified minimal stenosis in the internal carotid artery, whereas CEMRA gave the false appearance of severe stenosis because of the clip artifact described above. In the other patient, carotid ultrasound had revealed bilateral severe (70% to 99%) stenosis. However, both CEMRA and conventional angiography showed high-grade (80%) left internal carotid artery stenosis and moderate-grade (50%) right internal carotid artery stenosis.

Vertebral Artery Disease
Atherosclerotic disease of the vertebral artery was present in 119 patients was classified as occlusion in 29, high grade in 39, moderate grade in 23, and mild grade in 28. Correlation between CEMRA and conventional angiogram was possible in 22 patients, and no discrepancy was found. Correlation between CEMRA and ultrasound in 11 of these 22 patients revealed a discrepancy between the 2 tests in 1 patient. In that patient, ultrasound indicated that a vertebral artery was occluded, whereas CEMRA showed it to be patent.

Carotid and Vertebral Artery Occlusion
In patients who had had catheter angiography, CEMRA documented occlusion of the carotid artery in 6 and occlusion of the vertebral artery in 3 patients. These results were in agreement with the findings on catheter angiography.

Dissection
CEMRA was used to evaluate whether arterial dissection was present in 85 of the 239 patients with TIA and ischemic stroke. Of this group, 32 patients were shown to have cervical carotid and/or vertebral artery dissection and 11 patients were shown to have pseudoaneurysm by CEMRA. It was possible with CEMRA to demonstrate recanalization of a previously occluded artery and pseudoaneurysm formation or disappearance (Figure 3). Of the 85 patients, 14 underwent conventional angiography; in 12 of those 14 patients, the dissection that was identified on CEMRA was confirmed at conventional angiography. In 1 patient, dissection was suggested by CEMRA, but this was not confirmed by conventional angiography. In another patient, the arteries appeared normal on CEMRA, but conventional angiography performed 2 days later showed irregularity of the vertebral arteries at the C2 level, suggestive of dissection.

Discussion
Since 1999, CEMRA has been used widely in our clinical practice; consequently, the use of conventional catheter angiography has decreased greatly. As a reflection of the increasing confidence in CEMRA, only 12 of the 97 patients (12%) who had CEA also had catheter angiography. CEMRA provided additional information regarding the cervical arteries in 22% of the patients compared with ultrasound. This additional information changed the decision as to whether to proceed with CEA in 3% of the patients. As surgeons and
neurologists become increasingly comfortable with the use of CEMRA, we expect the use of catheter angiography to decrease still further.

CEMRA is an advance over 2D and 3D TOF MRA for the evaluation of the carotid arteries. An earlier study determined that a signal void on a 2D TOF MRA correlated with an angiographic diameter stenosis of $\geq 70\%$. These findings were based on the NASCET measurement technique. For the detection of angiographic stenosis of 70% to 99%, 3D TOF MRA demonstrated a sensitivity of 88%, a specificity of 89%, and an accuracy of 89%, whereas ultrasound, although it had a higher sensitivity, 97%, had a lower specificity and accuracy, 75% and 83%, respectively.

TOF MRA relies on flow-related enhancement to depict vessels and thus provides information about flow characteristics, analogous to ultrasound. When the cervical arteries are tortuous, signal loss may occur on TOF MRA because of the saturation and/or dephasing of spins. This does not occur with CEMRA because the contrast agent fills the vessel, as in catheter angiography. The sensitivity of CEMRA to slow flow allows detection of ulcerated plaque. Additionally, one can quantify the degree of stenosis more accurately with CEMRA than with TOF MRA. The use of TOF MRA may underestimate the degree of carotid stenosis because the short T1 of carotid plaque can cause a high signal and can mask signal loss on the maximum-intensity-projection display images. CEMRA did not have this type of T1-related artifact.

Previously, noninvasive evaluation of occlusive disease of the vertebrobasilar circulation was less than satisfactory. Imaging of the vertebrobasilar vessels was limited to a 3D TOF MRA of the circle of Willis and a 2D TOF study of the cervical component of the vertebral arteries. Vertebral artery origins and proximal portions were not typically visualized. Problems with this type of imaging arise in the upper cervical vertebral arteries, where flow in the axial plane caused signal loss. Artifacts of this type are much less conspicuous on CEMRA because of the short T1 of the contrast agent. Additionally, atherosclerotic disease involving the vertebral artery origins, an important source of clinical symptoms, can now be demonstrated with CEMRA.

Because catheter angiography was not performed in all patients in this study, the true sensitivity and specificity of CEMRA Vertebral Catheter Angiography Diagnosis

<table>
<thead>
<tr>
<th>CEMRA Vertebral Diagnosis</th>
<th>Catheter Angiography</th>
<th>Diagnosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild bilateral VA stenosis</td>
<td>Agree with CEMRA</td>
<td>R carotid angioplasty</td>
</tr>
<tr>
<td>Occluded proximal L and R VA, severe L subclavian stenosis</td>
<td>ND</td>
<td>No CEA</td>
</tr>
<tr>
<td>Normal</td>
<td>ND</td>
<td>No CEA</td>
</tr>
<tr>
<td>Proximal L VA stenosis</td>
<td>ND</td>
<td>Anticoagulation</td>
</tr>
<tr>
<td>Occluded R VA</td>
<td>ND</td>
<td>Carotid territory TIA, L CEA</td>
</tr>
</tbody>
</table>

Figure 2. Patient is a 58-year-old woman with a previous left CEA and 2 episodes of left amaurosis fugax. A, A 2D TOF study shows apparent signal voids at the left carotid bifurcation (arrow) and in the proximal internal carotid artery (curved arrow). B, CEMRA shows irregularity but no hemodynamically significant vessel narrowing at the origin of the left internal carotid artery (arrow), but a signal void suggests an extremely tight stenosis in the proximal left internal carotid artery (curved arrow). C, Conventional angiogram demonstrates that the areas of apparent stenosis are a result of artifacts caused by clips placed during a previous CEA. D, CEMRA of the aortic arch shows occlusion of the proximal left subclavian artery consistent with a subclavian steal syndrome (arrow). E, Left subclavian steal syndrome was confirmed on the conventional angiogram, where there is filling of the aortic arch and only a remnant of the left subclavian on the early arterial image (arrow). F, Delayed imaging shows retrograde flow through the left vertebral artery, resulting in filling of the left subclavian artery.

CEMRA for the determination of cervical artery dissection cannot be determined from our results. A caveat to the use of CEMRA is that a kink in the carotid artery may be confused with atherosclerotic plaque.
Occlusive disease of the aortic arch, such as Takayasu arteritis, can be adequately imaged with CEMRA. Also, subclavian steal phenomenon can be adequately demonstrated by this method and can be confirmed with directionally sensitive 2D PC used during the same examination. Often, this requires an additional coil, such as a torso phased-array coil. The ability to image aortic arch, proximal carotid, and vertebral artery disease, all noninvasively, provides the clinician with a powerful tool with which to study the mechanism of ischemic stroke and TIA within a single imaging session.

A patient’s having had a prior CEA does not degrade the performance of CEMRA. However, placement of a surgical clip at CEA can result in a susceptibility artifact, possibly leading to a false-positive diagnosis of stenosis. CEMRA was comparable to catheter angiography for the detection of vessel occlusion. Of the patients who underwent both CEMRA and conventional angiography, CEMRA demonstrated 6 carotid and 3 vertebral artery occlusions. All 9 of these vessel occlusions were confirmed by conventional angiography. No vessels characterized as patent on CEMRA were found to be occluded with conventional angiography. However, in an earlier study comparing the 2 imaging modalities, false-positive results were present on both CEMRA and catheter angiogram when surgical findings were used as the gold standard.

From a technical standpoint, we have found that the use of either fluoroscopic triggering or test bolus timing in conjunction with the elliptic centric-view ordering is crucial for obtaining good arterial enhancement and maximal suppression of venous structures. A power injector is essential, especially when a test bolus is used. The power injector provides uniform and reproducible flow rates between the test and bolus injections. The technical quality of the examination benefits from operator experience, which increases with the number of CEMRA exams performed. Other factors that may compromise image quality include large body habitus, poor venous access, and uncooperative patients.

In conclusion, the use of CEMRA permits noninvasive evaluation of patients with cerebrovascular disease. It offers good spatial resolution without the complications of catheter angiography. In some instances, as outlined above, catheter angiography may be required to confirm an abnormality. For mass screening purposes, CEMRA is not yet ideal because of the higher cost compared with ultrasound and the requirement that an MR scanner be available.

Acknowledgment
This work was supported by research grants CA-37993 and HL-37310 from the National Institutes of Health.

References
Contrast-Enhanced Magnetic Resonance Angiography of the Cervical Vessels: Experience With 422 Patients
Thanh Phan, John Huston III, Matthew A. Bernstein, Stephen J. Riederer and Robert D. Brown, Jr