Background and Purpose—The management of carotid atherosclerosis is well-established for symptomatic stenosis above 69%, but the optimal approach for managing lower degrees of narrowing remains uncertain. Because the risk of stroke increases with higher grades of stenosis, we are inclined to consider low-grade disease to be low risk. This approach, however, does not take into account other factors such as plaque size or composition. Plaque may progress to a substantial size before it demonstrates significant stenosis by angiography. We know that low-grade disease can result in cerebrovascular ischemic events, but predicting vulnerable lesions has not been possible by relying on stenosis alone.

Summary of Review—An understanding of the clinical behavior of plaque causing little to no narrowing is now possible with the advent of high-resolution black blood MRI, a modality that does not rely on luminal narrowing for detection.

Conclusion—We present the current understanding of the clinical implications of low-grade carotid stenosis with an example of the MRI assessment of high-risk carotid plaque causing minimal narrowing that highlights the importance of looking beyond the lumen. (Stroke. 2005;36:2504-2513.)

Key Words: atherosclerosis • carotid arteries • carotid stenosis • MRI • symptomatic carotid stenosis

Angiography has become the standard for assessing the risk of stroke from carotid atherosclerosis and determining the need for surgical intervention. This assessment relies on detecting hemodynamically significant narrowing based on the outcomes of randomized clinical trials such as the North American Symptomatic Carotid Endarterectomy Trial (NASCET) and the European Carotid Surgery Trial (ECST). These trials demonstrated a significant reduction in stroke risk with carotid endarterectomy compared with medical management for individuals with cerebrovascular symptoms attributable to narrowing above 69%. This helped to establish luminal narrowing as the primary measure of stroke risk on which management decisions are based.

Although the value of angiography is recognized for more advanced disease, its reliability for predicting the benefit of surgery for lower-grade narrowing remains less clear, particularly for those with 30% to 69% stenosis. Barnett et al4 reported a 5-year rate of ipsilateral stroke of 15.7% in individuals with 50% to 69% symptomatic stenosis treated with endarterectomy compared with 22.2% for those treated medically (P=0.045). For those with <50% stenosis, the rate was lower for those treated surgically (14.9% versus 18.7%, P=0.16). Reanalysis of the ECST study to allow comparison with NASCET showed a similar modest reduction in 5-year absolute risk in the 50% to 69% group treated surgically (5.7%; 95% confidence interval [CI], 0% to 11.6%). In this reanalysis, surgery had no effect on outcome in symptomatic patients with 30% to 49% stenosis. Additional randomization and longer follow up showed the stroke-free life expectancy within an 8-year follow-up period was shorter for surgery patients with 30% to 49% stenosis (6.16 versus 6.63 years for the nonsurgical group) and for surgery patients with 50% to 69% stenosis (5.93 versus 6.14 years for the nonsurgical group). The ECST trial found very little 3-yr risk of ipsilateral ischemic stroke for symptomatic individuals with 0% to 29% stenosis, even in the absence of surgery.

The risk of stroke from plaques causing low-grade narrowing in asymptomatic individuals is even less well understood. The Asymptomatic Carotid Atherosclerosis Study (ACAS) showed a reduction in the aggregate risk for stroke and perioperative stroke or death over 5 years to be 53% (95% CI, 22% to 72%) for patients with 60% or more carotid narrowing treated surgically compared with those treated medically. This study included only asymptomatic individuals with carotid narrowing >59%. Identification of asymptomatic individuals with low-grade narrowing who would benefit from surgical management would necessitate a highly specific method for stratifying risk not achievable by angiography considering the high prevalence of low-grade disease.

It is important to recognize that a nonsignificant reduction in risk by surgery for low-grade (ie, <50%) symptomatic stenosis does not imply these individuals are risk-free, but...
rather than that the risk of surgery exceeds the stroke risk with medical management. These individuals had events to be included in these analyses despite their low-grade narrowing. Furthermore, the prevalence of low-grade carotid stenosis is very high. The Cardiovascular Health Study detected carotid stenosis in 75% of men and 62% of women over 64 years of age by ultrasound, although prevalence of stenosis above 49% was only 7% in men and 5% in women. Therefore, although the risk of stroke with <50% carotid stenosis is low, the attributable risk for stroke resulting from <50% carotid stenosis may be significant as a result of the high prevalence of this finding.

The Need to Look Beyond Stenosis
We know from studies of coronary arteries that plaque rupture occurs at low degrees of narrowing and the degree of narrowing poorly predicts events. Ambrose et al retrospectively assessed angiograms of 38 subjects, 23 of whom had a subsequent myocardial infarction (MI), and found that the median stenosis on the initial angiogram of an artery that later caused an infarction was 48%. This is in contradistinction to 73.5%, the median narrowing of vessels that subsequently occluded but did not lead to a MI. Only 22% of the lesions that related to a subsequent infarction were narrowed >70%, whereas 61% of lesions that occluded but did not lead to an infarction measured >70%. Little et al reviewed coronary angiograms both before and up to 1 mo after an acute MI in 42 patients. The authors found that 19 of 29 newly occluded vessels had <50% stenosis on the initial angiogram. In 28 of 29, the stenosis was <70%. Plaque disruption may be more common at lower degrees of narrowing because of the higher stresses experienced by the fibrous caps compared with more stenotic plaques. This can be explained by the greater tension created in the caps of plaques causing mild to moderate stenosis compared with that created in caps of more severely stenotic plaques with the same cap thickness and at the same blood pressure based on Laplace’s law.

Although retrospective angiographic studies of extracranial carotid atherosclerosis and stroke have not been reported, the mechanism of plaque rupture may be similar to that seen in coronary arteries. The mechanism of stroke related to carotid atherosclerosis can be the result of hemodynamic factors or artery-to-artery embolism, but the initiating event still involves plaque rupture. In the case of high-grade carotid artery stenosis, it may be that plaque rupture results in vessel occlusion, but in low-grade carotid stenosis, plaque rupture theoretically may result in microembolism. In addition to plaque rupture, factors such as slow flow or a hypercoagulable state contribute to the likelihood of symptoms for more advanced carotid disease.

Uncovering Plaque Size and Risk: Limitations of Angiography
It is well established that human arteries remodel during early plaque formation, thereby maintaining the luminal area. Glagov et al demonstrated in coronary arteries that luminal encroachment does not begin until plaque has occupied 40% of the area circumscribed by the internal elastic lamina. This remodeling accounts for the inability of angiography to detect early atherosclerotic lesions and for its underestimation of plaque size in more advanced disease. This underestimation of plaque burden by angiography has been confirmed in carotid atherosclerosis by endarterectomy specimen correlates. Furthermore, angiography generally measures narrowing at the most severe point relative to adjacent sites that are considered normal. This does not account for the diffuse-ness of atheroma and further underestimates its burden.

The clinical implications of plaque size are less well understood than that of stenosis. The relationship between plaque size and stroke is also poorly understood in the carotid artery, although we suspect there are features of low-grade disease that predispose to events. For example, Weinstein found that hemorrhage and ulceration were strongly associated with symptoms despite many having 50% or less internal carotid artery stenosis.

Plaque Progression Through Repeated Silent Ruptures
More than 75% of thrombi responsible for acute coronary syndromes arise from plaque disruption. The morphologic characteristics of coronary plaques that rupture consist of a lipid-rich necrotic core and a thin fibrous cap rich in macrophages and T-cells with focal disruption. Reports of the mean necrotic core size seen with plaque rupture related to sudden coronary death range from 34% to 50%. These plaques are highly vascularized (vasa vasorum). Carotid atheromas follow a similar pattern of disruption, with fibrous cap foam cell infiltration and thinning and neovascularity also influencing the likelihood of rupture.

Morphologic studies of coronary arteries suggest that plaque progression beyond 50% cross-sectional–luminal narrowing occurs secondary to repeated ruptures, which may be clinically silent. The sites of healed plaque ruptures (HPR) can be recognized by demonstrating a necrotic core with a discontinuous fibrous cap, which is rich in type I collagen and an overlying neointima formed by smooth muscle cells in a matrix rich in proteoglycan and type III collagen (Figure 1).

Few angiographic studies have demonstrated plaque progression, and short-term studies have suggested that thrombosis is the likely cause. Mann and Davies showed that the frequency of HPRs increases along with lumen narrowing. Burke et al found HPRs in 61% of hearts from sudden coronary death victims. Multiple HPRs with layering were common in segments with acute and healed ruptures, and the percent cross-sectional luminal narrowing was dependent on the number of healed repair sites. The underlying percent luminal narrowing for acute ruptures exceeded that for healed ruptures (79 ± 15% versus 66 ± 14%; P = 0.0001). Therefore, the progression of atherosclerotic disease to severe stenosis is the result of repeated ruptures. At least 40% to 50% of coronary rupture sites show <50% diameter stenosis, and the same may be true in carotid disease. Spagnoli et al reported a higher incidence of thrombosis in patients with recent stroke as compared with asymptomatic individuals. However, it is uncommon to see thrombi occupying large
portions of the lumen in carotid ruptures12 (Figure 2), whereas in coronary artery disease, progressive narrowing is seen because of thrombosis.23

**Plaque Assessment by MRI**

We are interested in examining these same features in carotid plaques through noninvasive imaging, namely MRI. Ultrasound has also proven to be valuable for plaque characterization and assessment of stroke risk27–29; however, soft tissue discrimination is less robust with lipid core and intraplaque hemorrhage appearing the same,30 and heavy calcification can obscure plaque visualization.31 The advent of MRI has allowed for delineation of carotid atheroma, including the outer wall, thereby accounting for compensatory remodeling that accompanies its formation (Figure 3). MRI also discriminates morphologic features of atheroma that can provide insight into its vulnerability to rupture such as its fibrous cap and lipid core (Figure 4). In vitro studies have validated the ability of MRI to discriminate the major components of atheroma, including fibrous cap, lipid core, and calcium.32 Recent reports have demonstrated that carotid plaque calcification detected by computed tomography (CT) is associated with plaque stability.33,34 Although CT is generally more sensitive to calcium detection compared with MRI, Clarke et al35 reported a sensitivity of 97.6% for calcium detection in carotid plaque specimens in vitro by MRI using micro-CT as the standard. Application of these techniques in vivo is supported by the strong agreement demonstrated between in vivo and ex vivo measurements of vessel wall thickness and T2 relaxation of atheroma components.36,37

Wasserman et al38,39 showed improved conspicuity of the fibrous cap and outer wall after the intravenous administration of gadolinium. Areas of increased contrast enhancement within the cap might reflect sites of active inflammation that indicate impending rupture or reflect neovascularity seen with plaque instability.22,40

**High-Resolution MRI for Evaluation of Low-Grade Carotid Stenosis**

**Clinical Applications**

The application of MRI for managing carotid atherosclerosis will depend on the results of ongoing, prospective, population-based studies that relate cerebrovascular events to MRI features of carotid atheroma. For low-grade carotid stenosis, high-resolution MRI has an immediate role in assessing plaque size in the setting of compensatory remodeling and in identifying the culprit lesion. A great clinical challenge faced with low-grade carotid stenosis ipsilateral to a cerebrovascular ischemic event is determining if the event is attributable to the lesion. Carotid atherosclerosis is strongly associated with disease elsewhere, including the aortic arch, which is another source of cerebrovascular ischemic events. Shimizu et al41 showed that increased carotid intima to media thickness measurements are associated with complex aortic atheromas that are more likely to lead to embolic events. The low-grade carotid lesion is often overlooked as a source of such events because of presumed coexistent disease elsewhere and because the plaque size is underestimated as a result of vascular remodeling. Identifying a plaque as having been the source of a stroke may change its risk profile for future events. Inizitari et al42 showed that stroke risk in the territory of an asymptomatic carotid artery is substantially less than stroke risk in the territory of a symptomatic artery with a similar degree of stenosis. Dennis et al43 showed that patients who experienced a transient ischemic attack (TIA) had a 13-fold excess stroke risk during the first year and a 7-fold excess risk over the first 7 years compared with those
without TIAs. TIA might therefore be considered a warning for an impending cerebrovascular event and warrant investigation of the culprit lesion. Yuan et al and Murphy et al each demonstrated the ability of MRI to identify evidence for a recent TIA or stroke in carotid atheromas in vivo, although it should be noted that acute events were not studied in these reports. There have been no studies linking stroke to features of extracranial carotid atheroma causing low-grade stenosis partly because of the inability to identify these features before the advent of MRI and because large plaques with little hemodynamic effect are overlooked.

Case Illustration
We present a case that illustrates the application of MRI for assessing and managing low-grade carotid atherosclerosis. Mr. X is a 61-year-old man with medically managed hyperlipidemia who was well until August 2001 when he began experiencing episodic right arm numbness and weaknes and speech difficulties. He was admitted to an outside institution where brain MRI revealed multiple small areas of restricted diffusion in the left posterior watershed territory, consistent with multiple acute ischemic infarcts. Transesophageal echocardiogram revealed only echo-dense regions suggesting atherosclerotic plaque along the ascending aorta. The patient was hospitalized and treated with aggressive antithrombotic therapy but continued to experience episodes of right hemiparesis and hemisensory loss. He was eventually discharged on warfarin and clopidogrel. Cerebral angiography in mid-September was unremarkable except for irregularity of the left carotid bulb without significant luminal stenosis. Mr. X continued to have intermittent symptoms despite compliance with his medications.

In December 2001, Mr. X presented to our emergency room with transient right face, arm, and leg numbness and tingling. Diffusion- and perfusion-weighted brain MRI was negative for acute ischemia or perfusion abnormality. Because symptoms continued despite a therapeutic international normalized ratio on warfarin, the warfarin was stopped. He was maintained on clopidogrel and a statin agent.

Six days later, he was referred for MRI evaluation of his low-grade carotid narrowing. Informed consent was obtained for this and all future high-resolution MRI studies as part of a protocol approved by the local Institutional Review Board. Examinations were performed on a 1.5-T MRI scanner (GE Medical Systems) using a dual 3-in surface coil (GE Medical Systems) placed over his neck. A 3-dimensional time-of-flight MR angiogram (MRA) was acquired through the

Figure 3. Eccentric plaque formation without luminal narrowing detected by MRI in a 48-year-old man with a history of hypertension, cigarette smoking, and cocaine abuse. (A) Maximum intensity projection (MIP) of a CEMRA shows no narrowing despite eccentric plaque formation along the posterolateral wall of the internal carotid artery (A, thick arrow) with a thin inner lipid core (thin arrow) seen on the high-resolution contrast-enhanced BBMRI image (B) oriented through the bifurcation as shown in A (thin line).

Figure 4. Characterization of atheroma composition using high-resolution MRI. (A) In vivo contrast-enhanced BBMRI of the distal right common carotid artery of a 71-year-old man with asymptomatic carotid stenosis. Enhancing tissue highlights the relatively thick fibrous cap against the lumen and necrotic core (NC) as outlined in the schematic (B). The composition is confirmed in the endarterectomy section stained by Movat at the corresponding location (C). The specimen demonstrates a hemorrhagic NC containing calcifications (blue) with more dense calcifications (black) along its outer wall. Dark patches within the core seen on the MRI likely represent these focal calcifications. Note, part of the necrotic core and calcified areas has artifactually fallen off the section during cutting and staining.
carotid bifurcations. Black blood MRI (BBMRI) images were then acquired through the left carotid artery using a cardiac-gated, double inversion recovery fast spin-echo sequence with the inversion time adjusted based on heart rate to minimize blood pool signal. Imaging parameters are shown in the Table. An oblique proton density-weighted BBMRI image was oriented through the long axis of the carotid bifurcation using the MRA as a scout (Figure 5A), and this series was used to orient several T1- and proton density-weighted transaxial high-resolution BBMRI images through the plaque at the bifurcation (Figure 5B). Gadopentetate dimeglumine (Magnevist; Berlex Laboratories), 0.1 mmol per kilogram of body weight, was injected intravenously and a 3-dimensional contrast-enhanced MRA (CEMRA) was acquired during the arterial phase (Figure 5C).

Although the CEMRA showed no stenosis, a large plaque was identified on the long-axis BBMRI image through the bifurcation (Figure 5A and 5C). The transaxial BBMRI images through the plaque revealed an expanded outer wall flattening the adjacent jugular vein, accounting for the preserved lumen (Figure 5B). A small ulcer crater was seen along the distal plaque margin.

In May 2002, he returned for a duplex ultrasound study, which showed mild bilateral predominantly noncalcified plaque without stenosis in both carotid bulbs and internal carotid arteries. In July 2002, Mr. X returned for a repeat MRI evaluation (6-month follow-up study) of his left carotid artery using the technique described here. The CEMRA was unchanged. There was slight enlargement of the plaque with increased compression on the adjacent jugular vein (Figure 6). From a clinical perspective, the patient’s intermittent neurologic symptoms had stopped on clopidogrel alone.

Mr. X returned 6 months later for a third carotid MRI in January 2003. CEMRA again showed no stenosis and the plaque appeared slightly larger. The T1-weighted BBMRI sequence was repeated 5 minutes after contrast injection with adjustment of the inversion time to 200 ms to account for the reduced T1 relaxation of the blood pool. Chemical fat saturation was applied. These images showed linear enhancement along the luminal surface with some disruption centrally, and patchy enhancement deep within the atheroma (Figure 7). Mild irregularity of the luminal surface was seen in the region of enhancement. These findings were interpreted as a disrupted fibrous cap with inflammation or neovascularity deep within the atheroma.

In early October 2003, Mr. X had a prolonged episode of right arm and leg numbness and tingling with slight ataxia and right hand clumsiness. This was his first symptom in over 1 year. A brain MRI, performed 9 days later, revealed a focus

| MRI Imaging Parameters for the Black Blood Sequences |
|-----------------|-----------------|-----------------|
|                  | PD-Weighted     | T1-Weighted     |
|                  | Precontrast     | Postcontrast    |
| Slice thickness, mm | 2               | 2               | 2               |
| Gap              | 0               | 0               | 0               |
| Matrix           | 256×256         | 256×256         | 256×256         |
| Field of view, cm | 14              | 14              | 14              |
| TE, ms           | 6               | 6               | 6               |
| TR*              | 2RR             | 1RR             | 1RR             |
| TI, ms           | 600†            | 360†            | 200             |
| ETL              | 16              | 16              | 16              |
| NEX              | 1               | 1               | 1               |
| BW, kHz          | 62.5            | 62.5            | 62.5            |
| Scan time per slice, s‡ | 32             | 16              | 16              |

PD indicates proton density; TE, echo time; TR, repetition time; TI, inversion time; ETL, echo train length; NEX, number of excitations; BW, band width.

*The sequences were cardiac gated with the TR based on an RR interval of the cardiac cycle.

†The inversion time was automatically set (~600 ms) based on the heart rate to minimize the blood pool signal on the basis of estimated T1 values of blood.

‡Reported scan times are based on a heart rate of 60 beats/min. Times shorten with faster rates.

Figure 5. High-resolution MRI examination from December 2001 of the left carotid artery of a 67-year-old man with hyperlipidemia and left cerebral ischemic events beginning in August 2001. (A) Long-axis BBMRI image through the carotid bifurcation reveals a large plaque along the outer wall of the bulb (long arrows) narrowing the internal carotid artery lumen (*) with a small ulceration along its distal margin (short arrow). (B) Double oblique BBMRI image oriented through the plaque as shown in A (dotted line, A) demonstrates outward expansion of the plaque (black arrow) with compression of the adjacent jugular vein (arrowhead) and relative preservation of the internal carotid artery lumen (white arrow) corroborated by the insignificant narrowing seen on the CEMRA MIP (C). The small ulceration is again seen (white arrow). FD indicates flow divider.
of restricted diffusion in the superior left parietal lobe suggesting an acute infarction. In mid-November 2003, Mr. X returned for a repeat left carotid MRI evaluation. CEMRA was unchanged compared with all prior CEMRA studies. Transaxial images through the plaque revealed a soft tissue protuberance projecting into the lumen with its base at the site of mild luminal irregularity seen on the prior MRI (Figure 7). On postcontrast images, linear enhancement was seen along the luminal margin with disruption at the protuberance (Figure 7D). Patchy enhancement was seen deep within the atheroma and dense enhancement was seen within its lateral shoulder. The oblique BBMRI image through the bifurcation showed increased size of the ulcer crater. Mr. X had a catheter angiogram the next day that showed irregularity along the outer wall of the left carotid bulb but no significant narrowing.

After his cerebrovascular event in October, his neurologist recommended surgery for the following reasons: (1) repeated left hemispheric ischemic events, (2) irregularity on the conventional carotid angiogram suggesting ulceration, (3) MRI evidence of a culprit lesion (ie, evolving plaque surface features with a new protuberant tissue arising from the site of luminal irregularity following his recent stroke), and (4) absence of other etiologies for these stereotyped events. Even without the plaque MRI, it has been our policy to consider endarterectomy for \( \geq 50\% \) stenosis if the patient has an ulcerated plaque and repeated ischemic events despite maximal medical therapy. Mr. X elected to undergo endarterectomy.

In December 2003, Mr. X underwent an uneventful left carotid endarterectomy. The plaque was removed in one piece (Figure 8A) and serial cuts were made with sections oriented to correspond with the MRI image slices. The histologic...
Figure 8. Histologic analysis of endarterectomy specimen resected in December 2003 corresponding to plaque shown in Figures 5 through 8. (A) Gross bisected specimen. (B and C) Low-power photomicrographs of the carotid plaque at the rupture site stained by Movat and by Sirius red stains, respectively. (D) Boxed area in C showing the site of previous rupture under polarized light. This highlights the rupture site (arrow) in the type I collagen rich fibrous cap (yellow–pink) and the newly formed neointima, which is rich in type III collagen (green). (E) High-power view of the rupture site (larger boxed area in B). The ruptured fibrous cap is highlighted by black arrows and the thrombus (th) is seen in red at the site of the discontinuous cap. (F) High-power view of the smaller boxed area in B showing the previous rupture site with hemorrhage in the necrotic core and a small area of new intimal (ni) growth representing the healed thrombus, which is seen in Sirius red stain under polarized light as green in G. (H and I) Regions close to the fibrous cap showing macrophage infiltration by hematoxylin & eosin and CD68 stains, respectively. Red staining in H corresponds with hemorrhage, also seen as areas of red staining in B beneath the fibrous cap.
sections showed an eccentric plaque with a large necrotic core and plaque rupture located in the area of the positively remodeled artery. The fibrous cap was disrupted in its midportion and the thrombus was flush with the fibrous cap. The disrupted fibrous cap corresponded with the disrupted linear enhancement seen along the luminal surface of the plaque on the postcontrast MRI images (Figure 7D, middle image). At the shoulder region of the plaque, a healed rupture site was identified on Movat and Sirius red stains (Figure 8). This corresponded to the dense enhancement seen along the lateral shoulder of the plaque on the postcontrast images (Figure 7D, arrowhead). This HPR was likely the source of the ischemic events that led to his presentation in December 2001. The deeper patchy enhancement seen in Figures 7B and 7D corresponded with plaque inflammation with macrophage infiltration in an area of interspersed hemorrhage (Figure 8). Since his surgery in 2003, Mr. X has remained without recurrent neurologic symptoms through September 2005.

**Limitations of MRI for Plaque Assessment**

The clinical applicability of MRI imaging of plaque must be considered in light of several limitations of this modality. The resolution of MRI is limited by the available signal of the tissue of interest. Surface coils dedicated to carotid imaging provide a substantial gain in signal that enables acquired in-plane spatial resolution on the order of 500 μm.38,46 For coronary plaque, a cap is considered thin when it measures <65 μm.49 Although an equivalent measurement for the fibrous cap of carotid plaque has not been reported, it is likely <200 μm based on the relative size difference between coronary and carotid vessels. Therefore, MRI may falsely identify a thin or ruptured fibrous cap if the signal of the cap is not sufficient for it to be resolved. This limitation may become less relevant with further experience with contrast administration and with the development of high field magnets, because these advances may augment the signal of the cap enough for it to be identified even when thin.38 It should also be noted that vulnerable features that have been demonstrated in carotid plaques of patients who have had a recent TIA or stroke such as a thin cap as reported by Yuan et al44 or thrombus as reported by Murphy et al45 remain of uncertain value for prospective assessment of stroke risk. To date, there have been no reports demonstrating the clinical implication of an unruptured thin cap, although this underscores the importance of prospective MRI studies.

MRI also suffers from longer scan times relative to other modalities. Although plaque assessment can provide new information not achievable by angiography, each slice may take ≈20 seconds, which becomes more restrictive when broader coverage is needed such as imaging a 2-cm long plaque using standard 2-mm thick slices. The additional time becomes even more burdensome when the examination is in the setting of an acute stroke. This underscores another limitation of high-resolution MRI imaging, which is its restriction to a single plaque or vascular segment. The imaged plaque may show evidence for stability, whereas a neighboring plaque is about to disrupt and lead to a clinical event. Although angiography tells us nothing about the vulnerability of a plaque, it allows a survey of luminal narrowing that covers a wide area in a relatively short time, and the risk of a plaque causing high-grade stenosis detected by angiography is well established. A major challenge to using MRI for identifying plaque that causes little narrowing but is at risk for rupture is knowing where to image. This may be less a problem for carotid disease because carotid plaque ruptures in a more consistent location (ie, the bifurcation) than is true for other vascular beds. Furthermore, newer sequences allow for broader coverage in considerably less time and may enable a “high-resolution survey” of a large vascular segment.47

**When to Image Low-Grade Carotid Narrowing With MRI**

The high prevalence of low-grade carotid stenosis makes MRI as a screening tool economically prohibitive unless clinical markers are discovered that relate carotid atheroma to risk of future stroke for this population with little narrowing. For example, there is growing evidence that serum myeloperoxidase may serve as a prognostic indicator of near-term cardiovascular events,48 and this is one of several markers that is undergoing investigation presently. Until such markers are identified, the application of MRI for assessing low-grade carotid disease is best suited for individuals who experienced a cerebrovascular ischemic event in the vascular territory of the stenotic extracranial carotid artery. As we become more knowledgeable of the clinical implications of MRI features of atheroma, the workup of stroke with ipsilateral carotid artery narrowing may include a high-resolution MRI survey of the composition of bifurcation plaque, if present, in addition to the standard MRA evaluation.

**Implications of High-Resolution Plaque MRI**

Once a carotid plaque causing low-grade stenosis has been identified as a potential culprit lesion by high-resolution MRI, the appropriate choice of management must be considered. In the absence of compelling data from the NASCET and ECST studies to justify the risk of surgery for low-grade disease, the standard approach remains maximizing medical therapy. Now that technology exists to identify morphologic and surface features of vulnerability in low-grade carotid atheroma, further studies are needed to better understand the clinical implications of these features in this population. For now, the detection of plaque vulnerability, or recent rupture like in our case by MRI may suggest stroke risk for an individual plaque despite its effect on the lumen.

It is important to recognize that an individual plaque must be considered part of a systemic disease and that endarterectomy addresses only one lesion. Carotid intima to media thickness measured by ultrasound is an independent predictor of incident cardiovascular events even after adjustment for traditional risk factors in older adults without preexisting cardiovascular disease.49 The greater clinical implication of identifying a vulnerable carotid atheroma with little hemodynamic effect might be the insight it provides regarding vulnerable disease elsewhere rather than the future risk for that lesion. Plaque vulnerability may be a systemic process, and the structure of a carotid atheroma might reveal the vulnerability of the patient as a whole.50,51 Furthermore, carotid atheroma causing little luminal narrowing may be at...
an earlier stage when medical therapy or lifestyle modification can have a greater impact.52

Summary
MRI has emerged as a tool capable of uncovering and characterizing atheroma before it has a hemodynamic effect on the lumen, allowing a means to study factors associated with risk for rupture. Identifying and characterizing lesions that had since gone unrecognized by angiography forces us to reconsider our guidelines for managing low-grade carotid stenosis. We recognize that much of our speculation about carotid disease is based on extrapolation from data on coronary atherosclerosis; however, we hope that MRI will allow us to study these same processes in carotid artery plaque. We await the results of ongoing population-based, prospective studies to determine the significance of MRI features of atheroma for assessing stroke risk prospectively. Presently, MRI offers a tool that can identify the culprit lesion, a particular challenge with low-grade disease, creating management decisions not previously faced. The greater value of this method might be in using it to gauge disease elsewhere with the carotid artery serving as a window to the cardiovascular system. Ultimately, understanding the nature of atherosclerosis formation in the carotid artery might allow us to identify the vulnerable patient in whom systemic intervention could be initiated to prevent cardiovascular events.

Acknowledgments
This study was supported in part by the Johns Hopkins University School of Medicine General Clinical Research Center grant no. M01-RK00052 from the National Center for Research Resources/NIH. The authors thank Rena Geckle for her tremendous assistance.

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low-grade carotid stenosis: Assessment with MRI


Low-Grade Carotid Stenosis: Looking Beyond the Lumen With MRI
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Stroke. 2005;36:2504-2513; originally published online October 20, 2005;
doi: 10.1161/01.STR.0000185726.83152.00
Stroke is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2005 American Heart Association, Inc. All rights reserved.
Print ISSN: 0039-2499. Online ISSN: 1524-4628

The online version of this article, along with updated information and services, is located on the
World Wide Web at:
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