Evaluation of carotid artery atherosclerotic plaque distribution by using long-axis high-resolution black-blood magnetic resonance imaging

Clinical article

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Object. The goal of this study was to evaluate the usefulness of long-axis black-blood MR (BB–MR) imaging for assessing plaque morphology and distribution in patients with atherosclerotic carotid artery (CA) stenosis. Methods. Sixty-eight carotid arteries in 67 patients who were scheduled to undergo CA endarterectomy or CA stent placement due to atherosclerotic stenosis were included in this study. The patients had undergone CA BB–MR imaging and digital subtraction (DS) angiography within 3 weeks of revascularization. The DS angiography studies were performed using the transfemoral artery approach with selective common CA catheterization. The BB–MR images were acquired using a 1.5-T whole-body MR imaging unit, and T1-weighted images parallel to the long axis of the artery at 1-mm intervals were obtained. Plaque distribution was evaluated by measuring the distance between the CA bifurcation and the point that appeared to be the distal extent of the plaque on BB–MR imaging (D–MR imaging) and DS angiography images (D–DS angiography). Results. Plaque distribution was clearly shown in 88.2% of the cases using long-axis BB–MR images, except for 8 arteries with poor image quality. In 4 arteries, D–DS angiography could not be obtained because the distal plaque end could not be confirmed. In 56 vessels, both the D–DS angiography and D–MR imaging could be measured; the mean D–MR imaging (19.75 ± 6.85 mm [standard deviation]) was significantly longer than the average D–DS angiography (16.32 ± 7.07 mm). Conclusions. Long-axis BB–MR imaging can provide a noninvasive and accurate way to show CA plaque distribution; it is of great use not only for stroke risk assessment in patients with CA atherosclerosis but also for preoperative evaluation in patients requiring CA endarterectomy or CA stent placement. (DOI: 10.3171/JNS.2008.109.12.1042)

Key Words • atherosclerosis • carotid stenosis • magnetic resonance imaging • plaque morphology

The benefit of CEA in patients with high-grade CA stenosis has been definitely proven by several large multicenter trials.2,4,8,15 Recently, the usefulness of CAS for atherosclerotic CA stenosis as an alternative to CEA has also been demonstrated by randomized studies,27 and the advantages and disadvantages of each revascularization procedure are currently under discussion.1,24,29 Based on the results of randomized trials, the indications for CA revascularization have been basically determined by luminal narrowing, irrespective of the type of intervention.24,8,15 In clinical practice, several diagnostic modalities, such as ultrasonography, CT angiography, and MR angiography, are used to assess the stenosis rate; conventional DS x-ray angiography is the gold standard.

It has been found that not only the severity of stenosis but also plaque stability plays an extremely important role in the association between CA atherosclerosis and the risk of stroke.5,9,25,33 According to the results of recent vascular biology studies, plaque stability depends on several factors, such as plaque components, volume, and morphological characteristics. Furthermore, it is generally accepted that the atherosclerotic vessel wall can compensate for luminal narrowing by means of expansive arterial remodeling13,26,27 and that patients with CA plaque, even those in whom luminography reveals no significant stenosis, are at risk for stroke. Therefore, the importance of evaluating the vessel wall itself has been increasing in the management of CA stenosis. Ultrasonography is

Abbreviations used in this paper: BB = black-blood; CA = carotid artery; CAS = CA stent placement; CEA = CA endarterectomy; DS = digital subtraction; ICA = internal CA; NASCET = North American Symptomatic Carotid Endarterectomy Trial.
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widely used to diagnose CA stenosis; it is noninvasive and provides information on luminal narrowing and, to some extent, plaque characteristics. For the evaluation of CA circulation, ultrasonography has some limitations. Plaque with dense calcification, a CA with marked meandering, and a stenosis at a high position cannot be fully imaged by means of CA ultrasonography; furthermore, the interpretation of the results is strongly operator-dependent.6,17

Recently, many studies have demonstrated the feasibility of using high-resolution MR imaging as a noninvasive and non–operator-dependent modality for CA wall evaluation.31,34,42 Using axial images with high-resolution MR imaging, it is possible to not only measure total plaque volume42 but also to characterize plaque components, such as the fibrous cap and the lipid core, as well as the presence of hemorrhage and calcification.34 It is thought that, in the near future, stroke risk will be assessed more precisely based on several factors such as stenosis rate, plaque morphology, and plaque characteristics. Such a risk-stratification strategy of atherosclerotic CA disease would be of great importance when considering the indications for CEA or CAS in patients who have moderate stenosis with a vulnerable plaque or in patients who have considerable stenosis with a stable plaque.

The aim of the present study was to evaluate the usefulness of long-axis, high-resolution, BB–MR imaging for assessing plaque morphology and wall disease burden in patients with atherosclerotic CA stenosis.

Methods

Patient Population

A total of 68 consecutive CAs in 67 patients, who were scheduled to undergo CEA or CAS due to atherosclerotic CA stenosis and preoperatively underwent both carotid BB–MR imaging and DS angiography, were included in this study. For all patients, intervals between carotid BB–MR imaging and DS angiography were ≤ 2 weeks. There were 39 symptomatic and 29 asymptomatic vessels. The degree of stenosis according to the NASCET DS angiography criteria was 73.7 ± 16.8% (mean ± standard deviation). Inclusion criteria for revascularization were ≥ 70% carotid stenosis or < 70% symptomatic stenosis with recurrent infarcts on the ipsilateral hemisphere refractory to maximal medical treatment. With regard to risk factors for cerebral infarction, the prevalence of hypertension, diabetes, hypercholesterolemia and coronary heart disease was 69, 34, 45, and 31%, respectively.

The study was approved by the hospital ethics committee, and written informed consent was obtained from all patients.

Imaging Techniques

The DS angiography images were acquired using a biplane angiography machine (Integris Allura 12/12, Philips Medical Systems). The DS angiography studies were performed using a transfemoral artery approach and selective common CA catheterization. Images were obtained in anteroposterior and lateral projections. Additional projections were added, if needed, to better demonstrate the CA bifurcation and stenosis. The DS angiography was performed with a 22-cm field of view and a 1024 × 1024 matrix. The spatial resolution was 0.21 × 0.21 mm.

Carotid artery BB–MR images were acquired using a 1.5-T whole-body MR imaging unit (Gyroscope Intera, Philips Medical Systems) with an 8-cm surface coil. Cardiac-gated T1-weighted images of sagittal sections parallel to the long axis of the artery at 1-mm intervals were obtained using the double inversion recovery technique to suppress blood flow signal. The fat suppression method was applied to suppress marked signal hyperintensity due to subcutaneous fat tissue by using chemical shift–selective fat suppression technique of spectral presaturation with inversion recovery. The parameters of BB–MR imaging were as follows: 3D inversion-recovery turbo field echo, field of view 150 mm, matrix size 320 × 512, TR/TE/TI 10/2.7/500 msec, flip angle 35°, slice thickness 1.6 mm, and reconstructed voxel size 0.29 × 0.29 × 0.8 mm.

Image Review

The BB–MR imaging results were transferred to a computer workstation where they were reviewed by 2 investigators (K.Y. and H.E.) who were blinded to the results of the DS angiography studies. Based on the signal quality, the motion/flow artifacts, and the plaque–lumen interface differentiation, image quality was assessed by each observer using 3 grades: excellent, appropriate for diagnosis, and inadequate for diagnosis. Vessels in patients with inadequate image quality were excluded.

Plaque distribution was evaluated by measuring the distance between the CA bifurcation and the point that appeared to be the distal extent of the plaque on BB–MR imaging and DS angiography images. Using images in the lateral projection of the arterial phase on the workstation, the distance on the DS angiogram (D–DS angiography) was measured by an observer who did not know the results of the BB–MR imaging studies (Fig. 1A). With regard to the MR imaging studies, 2 long-axis images, each of which included the CA bifurcation (Fig. 1B) and the distal end of the plaque (Fig. 1C), were selected; then the distance between the 2 points when projected onto the same plane (D–MR imaging) was measured on the workstation using electronic calipers. The mean of the D–MR imaging readings obtained by the 2 investigators was taken as the final value for D–MR imaging.

Data pertaining to artery characteristics are expressed as means ± standard deviations. Statistical significance was calculated using the Tukey test; probability values < 0.05 were considered significant. All calculations were made with SPSS 12.0 for Windows.

Results

The BB–MR images from 8 cases were graded as inadequate for diagnosis by either of the investigators, and these cases were excluded from analysis. Poor image quality was due to motion artifact in 7 vessels and flow artifact with highly irregular luminal narrowing in 1 vessel. Thus the plaque distribution was clearly demonstrated with long-axis BB–MR imaging in a total of 60 carotid arteries (88.2%, Fig. 1).
In the DS angiography studies, 4 arteries in which the D–DS angiography could not be obtained because of inability to confirm the distal plaque end were excluded from analysis. Pseudoocclusion (Fig. 2) was present in 3 of these 4 arteries, and 1 artery was in a patient in whom DS angiography did not demonstrate substantial luminal narrowing (Fig. 3).

In 56 vessels, both the D–DS angiography and the D–MR imaging could be measured and used to evaluate the distal extent of plaque. The D–MR imaging was 19.64 ± 7.24 mm as measured by one of the authors who performed the measurements (K.Y.) and 19.86 ± 6.50 mm as measured by the other (H.E.); the difference was not statistically significant (p = 0.985).

The D–DS angiography and the final D–MR imaging values (the mean of the D–MR imaging values obtained by the 2 investigators) were 16.32 ± 7.07 and 19.75 ± 6.85 mm, respectively. The D–MR imaging was 21% longer than the D–DS angiography, and this difference was significant.

**Illustrative Case**

This 75-year-old man had been medically treated for hypertension and hyperlipidemia until August 2000 when he was admitted to our hospital with right arm and leg weakness, as well as a speech disturbance. Diffusion weighted images obtained on admission demonstrated multiple small high-signal spots in the left anterior border zone area, consistent with multiple acute infarcts. The left CA angiogram revealed no significant luminal narrowing but slight luminal irregularity (Fig. 3A). Long-axis BB–MR imaging clearly identified appreciable plaque burden in the form of expansive remodeling at the bifurcation (Fig. 3B). The strikingly high signal on T1-weighted images of the axial BB–MR imaging indicated the possible existence of abundant intraplaque hemorrhage (Fig. 3C).

Furthermore, the absence of a juxtaluminal band of low signal in the time-of-flight MR images suggested a thin or ruptured fibrous cap. No significant atherosclerotic plaque along the ascending aorta was detected on echocardiography, and there was no atrial fibrillation on Holter monitoring.

Based on the results of these examinations, a diagnosis of minor stroke due to artery-to-artery embolism originating from the unstable CA atherosclerotic plaque was decided upon; the patient was treated medically with aspirin. Aggressive antithrombotic therapy with aspirin and ticlopidine was administered after the patient developed a minor infarct in the ipsilateral hemisphere 22 months after the initial stroke. Nevertheless, the patient had 7 minor strokes over 5 years. The high signal on T1-weighted BB–MR imaging persisted during medical treatment.

Because not even maximal medical therapy could prevent stroke recurrence, in July 2005 the patient had CEA after written informed consent was obtained. The luminal surface of the excised plaque showed an extensively ruptured fibrous cap (Fig. 3D), and histological examination revealed massive intraplaque hemorrhage (Fig. 3E). The long-lasting high signal on T1-weighted images was the result of either continued fibrous cap disruption or successive fibrous cap rupture and restoration.
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CEA, the patient has been treated with aspirin only; to date, he has been stroke-free after 2 years of follow-up.

Discussion

This study shows the usefulness of BB–MR imaging for the noninvasive evaluation of the distribution of atherosclerotic CA plaque. Unlike CA ultrasonography, BB–MR imaging can provide objective assessment of the distal extent of the plaque, since it is unaffected by factors such as height of the CA bifurcation, vessel tortuosity, and the presence of dense calcification. The ability of BB–MR imaging to demonstrate the distal end of the plaque has paramount importance, especially when vascular reconstruction is being considered. Preoperatively, the extent of dissection can be determined for CEA cases, and the appropriate stent length and placement location can be chosen in CAS cases. Black-blood MR imaging can also clearly identify the CA without significant luminal narrowing but with abundant expansive atherosclerotic plaque—so-called positive remodeling (Fig. 3). The mechanism of stroke due to atherosclerotic CA disease can involve hemodynamic compromise or artery-to-artery embolism; in either situation, however, the trigger still involves plaque rupture. It is generally accepted that acute coronary syndrome frequently results from rupture of an atherosclerotic plaque with only mild-to-moderate luminal narrowing in patients with ischemic coronary artery disease; a mechanism of plaque disruption that is similar to that seen in the coronary arteries can also occur in patients with CA atherosclerosis. It is, therefore, of clinical importance to accurately diagnose CA atherosclerosis with positive arterial remodeling when considering the treatment for stroke prevention. In fact, the patient in our illustrative case (Fig. 3) had 7 minor strokes over a period of 2 years despite meticulous medical treatment.

The fact that D–MR imaging was ~ 20% larger than the D–DS angiography in this study suggests that the plaque can extend, either in a wedge-shaped fashion or due to expansion, beyond the point where luminal narrowing can no longer be seen on DS angiography. In fact, it can be occasionally observed in CEA that the end of the plaque is more distal than was expected based on the preoperative DS angiography. Therefore, long-axis images obtained by means of BB–MR imaging can more accurately confirm the distal extent of the plaque than DS angiography.

With the use of BB–MR imaging, not only the distal end of the plaque but also the collapsed lumen of the distal ICA can be clearly demonstrated, even in patients with CA pseudoocclusion in whom plaque distribution cannot be confirmed by DS angiography (Fig. 2). With respect to CA revascularization in patients with pseudoocclusion, several studies have reported that CEA for chronic pseudoocclusion is less beneficial, because sufficient restoration of the luminal narrowing in the distal ICA cannot be provided for several reasons, such as a long atheromatous occlusion, fibrotic change, or chronic subtotal thrombosis. Therefore, when considering the indications for direct CA revascularization, it is of prime importance to assess whether the distal ICA is simply collapsed or there is substantial arterial change, which cannot be evaluated by DS angiography. Several diagnostic modalities, such as transoral ultrasonography, enhanced CT, and intravascular ultrasonography during CEA, have been reported to be useful for assessing the distal ICA in cases of pseudoocclusion. Our results show that long-axis BB–
MR imaging is also very useful for evaluating pseudoocclusion, since it is noninvasive, accurate, and objective.

The present study of the assessment of plaque distribution using BB–MR imaging has several limitations. First, MR imaging cannot be performed in patients with medical devices such as pacemakers or patients who cannot rest quietly, as is often true of those who with an acute major stroke. Second, long-axis BB–MR imaging could not provide an evaluation of plaque burden due to poor image quality in ~ 10% of the MR imaging studies. Image quality was dependent on several factors, such as patient motion and flow artifact in patients with extreme luminal irregularity. Moreover, poor contrast at the lumen–vessel wall interface caused by incomplete flow signal suppression in the CA bifurcation can make it difficult to identify plaque on BB–MR imaging. With technological developments, such as flow suppression sequences and surface coil design, and improvements in spatial resolution and signal-to-noise ratio with the use of machines with stronger magnetic fields, image quality will be further improved, and BB–MR imaging will become an indispensable tool in clinical practice for assessment of plaque in cases with atherosclerotic CA disease.

**Conclusions**

Long-axis BB–MR imaging is a noninvasive and accurate method of showing the distribution of CA plaque; it is of great use not only for stroke risk assessment in patients with CA atherosclerosis but also for the preoperative evaluation of patients prior to CEA and CAS.

**Disclaimer**

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.
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References


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