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High-Intensity Signals in Carotid Plaques on T1-Weighted Magnetic Resonance Imaging Predict Coronary Events in Patients With Coronary Artery Disease

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Objectives

The purpose of this study was to determine whether high-intensity carotid plaques visualized by a noncontrast T1-weighted imaging technique, magnetization-prepared rapid acquisition with gradient echo (MPRAGE), predict future coronary events in patients with clinically stable coronary artery disease (CAD).

Background

Coronary plaque vulnerability to rupture can be assessed by examining for the presence of atherosclerosis and measuring intima media thickness (IMT) in surrogate vessels such as the carotid arteries. We previously showed that MPRAGE successfully identifies vulnerable carotid plaques as high-intensity signals. It remains unclear, however, if the presence of carotid high-intensity plaques (HIP) is associated with an increased risk of coronary events.

Methods

We examined the signal intensity of carotid plaques in 217 patients with clinically stable CAD using MPRAGE with magnetic resonance imaging and measured IMT with ultrasonography. A carotid HIP was defined as a signal >200% that of the adjacent muscle. All patients were divided into 2 groups according to the presence or absence of HIP, namely, the HIP group (n = 116) and the non-HIP group (n = 101), and were followed up for as long as 72 months.

Results

The presence of HIP was significantly associated with cardiac events compared to the non-HIP group (log-rank $p < 0.0001$). Furthermore, multivariate Cox regression analysis identified the presence of HIP as the strongest independent predictor of cardiac events (hazard ratio: 3.15; 95% confidence interval: 1.93 to 5.58, $p < 0.0001$) compared with IMT (hazard ratio: 1.62, 95% confidence interval: 0.97 to 2.44, $p = 0.055$) and other coronary risk factors.

Conclusions

Characterization of carotid plaques using magnetic resonance imaging with MPRAGE provides more clinically relevant information for the risk assessment of CAD patients than IMT. (J Am Coll Cardiol 2011;58:416–22)
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Rupture of vulnerable atherosclerotic plaques in the coronary vessels leads to acute coronary syndromes. Collectively, recent studies suggest that, rather than simply being a local vascular incident, plaque instability is a systemic problem present in multiple vascular beds throughout the body. Thus, it may be possible to assess the vulnerability of coronary artery plaques to rupture and the development of acute coronary syndromes by evaluating the stability and composition of plaques in other vessels (1–3). However, this has not been clearly estab-

lished, and prospectively identifying a high-risk coronary artery disease (CAD) population vulnerable to plaque rupture remains difficult.

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Magnetic resonance imaging (MRI) can be used to noninvasively assess carotid plaque characteristics in vivo. High-intensity signals observed in carotid plaques using inversion recovery-based 3-dimensional T1-weighted imaging—alternatively known as magnetization-prepared rapid acquisition with gradient echo (MPRAGE) (4) or magnetic resonance direct thrombus imaging (MRDTI) (5,6)—are associated with recent ischemic cerebrovascular events (6–8) and are related to complex plaques (type VI as proposed by the American Heart Association) (9,10). Several

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groups have used high-resolution multicontrast MRI to examine the relationship between plaque composition and cerebrovascular events, and their data suggest that MRI can successfully identify vulnerable carotid plaques (11–14). However, no studies have evaluated the relationship between carotid artery plaque vulnerability detected by MRI and subsequent coronary events. In the present study, we hypothesized that the presence of carotid high-intensity plaques (HIP) visualized by MPRAGE predicted future coronary events in patients with clinically stable CAD.

Methods

Patients. Between 2002 and 2005, 665 consecutive patients who underwent MRI with suspected or confirmed atherosclerosis of the carotid artery at our institute were considered for enrollment. The exclusion criteria for the study were acute myocardial infarction (AMI), unstable angina pectoris, severe valvular heart disease, end-stage renal failure, cardiomyopathy, and infectious, chronic inflammatory, and autoimmune diseases. Among the 665 possible patients, 226 had a history of CAD described in their medical records at our hospital. Stable CAD was defined as the absence of episodes of angina at rest on admission in patients with angiographically documented stenosis >50% in at least 1 of the major coronary arteries. Six patients who underwent coronary artery bypass surgery and 3 patients who were hospitalized for heart failure in the first 12 months of the study were excluded. Thus, a total of 217 patients with clinically stable CAD were ultimately enrolled in this study. This study conformed to the 2005 version of the Ethical Guidelines for Clinical Study (Ministry of Health, Labour and Welfare of Japan), and was approved by the ethics committees of the National Cardiovascular Center.

Magnetic resonance imaging. The MRI was performed on a 1.5-T clinical system (Magnetom Sonata, Siemens, Erlangen, Germany) with standard neck and spine array coils. Plaque imaging was performed using MPRAGE in transaxial sections using a null blood condition (effective inversion time 660 ms; repetition time [TR] 1,500 ms) and water excitation technique to suppress fat signals. The TR was defined as the interval between successive inversion pulses. Other imaging variables included echo time (TE) 5.0 ms; flip angle 15°; field of view 180 × 180 mm; matrix 256 × 204; slice thickness 1.25 mm; 56 partitions covering 70 mm around the carotid bifurcation; and data acquisition time 5 min. Multislab 3-dimensional time-of-flight magnetic resonance angiography (MRA) was also performed to determine lumen shape and plaque morphology with the following parameters: TE 4.4 ms; TR 35 ms; flip angle 15°. The spatial resolution parameters were the same as with MPRAGE. Contrast MRA was performed after MPRAGE and 3-dimensional time-of-flight MRA. Gadolinium diethylenetriamine penta-acetic acid (Gd-DTPA, Magnevist, Bayer-Schering AG, Berlin, Germany), 0.1 mmol/kg body

weight, was infused at a rate of 2.0 to 3.0 ml/s after a test bolus of 1 ml Gd-DTPA. Contrast MRA imaging parameters included TR 3.2 ms; TE 1.3 ms; slice thickness 1.0 mm; 64 partitions; field-of-view 360 × 200 mm; matrix 512 × 208; data acquisition time 14 s; near-coronal section. Carotid stenosis was measured using contrast MRA according to the methods defined by the NASCET (North American Symptomatic Carotid Endarterectomy Trial) (15).

The methods used to evaluate MR images in this study have been described previously (8). Briefly, an experienced radiologist (N.Y.) analyzed the carotid plaque signal intensity on MPRAGE relative to the adjacent muscle using a round region of interest (5 to 8 mm in diameter). Figure 1 shows representative cases with atherosclerotic plaques within the carotid arteries. Criteria for the assessment of hyperintense carotid plaques have been previously reported (8,16), and patients with plaques in either the right or left carotid artery in which any region of the plaque exhibited a signal intensity >200% of the adjacent muscle were placed in the “HIP group” (Fig. 1A). Otherwise, patients were placed in the “non-HIP group” (Fig. 1D). The κ values for interobserver and intraobserver agreement for the categorization of carotid plaques as HIP or non-HIP were 0.73 and 0.79, respectively (8).

Ultrasound evaluation. A carotid ultrasound examination was performed in the ultrasound laboratory using a 7.5-MHz, linear-array transducer (SSA-270A, Toshiba, Tokyo, Japan) shortly after admission but before MRI in all patients. Two operators performed all carotid scans, and they were unaware of the clinical characteristics of the patients. The common carotid arteries were imaged bilaterally in the anterior oblique, lateral, and posterior oblique planes to identify atherosclerotic lesions. On a longitudinal image of each common carotid artery, intima media thickness (IMT) was defined as the distance from the leading edge of the lumen-intima interface to the leading edge of the media-adventitia interface. The maximal IMT (IMT_{max}) was defined as the thickest region of the far walls of either the left or right common carotid artery. All measurements were performed in a centralized laboratory by 2 trained physicians who were unaware of the subjects’ clinical data. The interreader variability defined by Spearman correlation coefficients on maximum wall thickness of the common carotid artery was 0.90.

Abbreviations and Acronyms

AMI = acute myocardial infarction
CAD = coronary artery disease
CI = confidence interval
HIP = high-intensity plaque
HR = hazard ratio
hsCRP = high-sensitivity C-reactive protein
IMT = intima media thickness
MPRAGE = magnetization-prepared rapid acquisition with gradient echo
MRA = magnetic resonance angiography
MRI = magnetic resonance imaging
TE = echo time
TR = repetition time

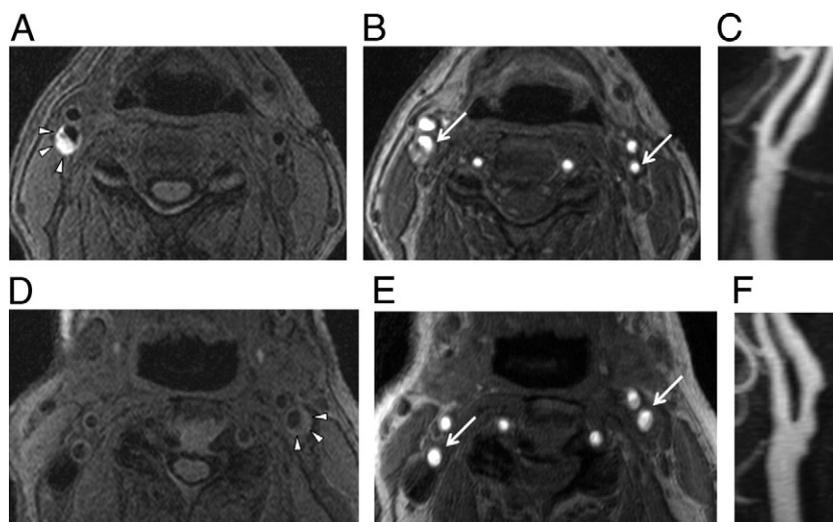


Figure 1 **Representative Plaque Images of Atherosclerotic Carotid Arteries**

In a patient with high-intensity plaques (HIP), (A) magnetization-prepared rapid acquisition with gradient echo (MPRAGE) displays hyperintensity signals in the thick plaque of the right internal carotid artery (arrowheads); (B) time-of-flight magnetic resonance angiography (MRA) displays no significant luminal stenosis of the internal carotid arteries bilaterally (arrows); and (C) contrast MRA of the right carotid artery shows no significant stenosis. In a patient lacking HIP, (D) MPRAGE displays isointensity signals in the plaques of the internal carotid artery bilaterally, and the plaque of the left internal carotid artery is thick (arrowheads); (E) time-of-flight MRA displays no significant luminal stenosis of the internal carotid arteries bilaterally (arrows); and (F) contrast MRA of the left carotid artery shows no significant stenosis.

Left ventricular function analysis. Left ventricular ejection fraction was measured by radioisotope image on single-photon-emission computed tomography before MRI in all patients.

Determination of serum C-reactive protein. High-sensitivity C-reactive protein (hsCRP) was assayed by latex nephelometry in fasting serum samples (SRL, Tokyo, Japan).

Follow-up study. After MRI data were obtained, the 217 patients with stable CAD were followed up at our hospital for a period for 12 to 72 months or until the occurrence of 1 of the following clinical coronary events: cardiac death, nonfatal AMI, unstable angina pectoris, or unplanned hospitalization for recurrent angina. Percutaneous coronary intervention-related restenosis was not considered a coronary event. Chart review was conducted by independent attending cardiologists to determine if subject hospitalizations and/or deaths qualified as primary endpoints of the study. These chart reviewers were blinded to the patients' HIP status. All stable CAD patients received standard medical therapy, as outlined in Table 1.

Statistical analysis. Continuous baseline variables with normal distribution were expressed as mean \pm SD and compared by unpaired *t* test. The Mann-Whitney *U* test was used to evaluate differences in IMT, hsCRP, and carotid artery stenosis. Categorical baseline variables were compared by Fisher exact test or chi-square analysis where appropriate. Survival analysis was carried out using the Kaplan-Meier method (log-rank test), according to the presence or absence of HIP. The data were analyzed initially using a univariate model to determine the risk

factors that had a significant association with future coronary events. Multivariate Cox regression analysis was then applied using only the covariates that significantly predicted coronary events in the univariate analysis. All analyses were conducted using SPSS (SPSS Japan Inc., Tokyo, Japan).

Results

Baseline clinical characteristics. The baseline clinical characteristics of the study patients are shown in Table 1. The median, first quartile, and third quartile range of carotid plaque signal intensity relative to the adjacent muscle was 3.10, 2.67, 3.63, respectively, in the HIP group; and 1.51, 1.39, 1.70, respectively, in the non-HIP group. The HIP group had significantly higher levels of hsCRP and low-density lipoprotein cholesterol, higher rates of multivessel CAD and previous MI, lower levels of high-density lipoprotein cholesterol, and increased IMT_{max} values. There was no significant difference in the degree of carotid artery stenosis between the 2 groups, and there were no differences in the administered medications between the 2 groups.

MRI of carotid artery and prognostic value of HIP in stable CAD patients. One hundred sixteen of the 217 patients were categorized to the HIP group. Figure 1 shows representative MR images of patients in the HIP group (Figs. 1A and 1B) and non-HIP group (Figs. 1D and 1E). Patients were followed up for a mean of 38.3 months. There were 31 coronary events in the HIP group during the follow-up period, but there were only 5 such events in the non-HIP group ($n = 101$; $p < 0.001$) (Table 2). When

Table 1 Comparison of Baseline Clinical Characteristics

	HIP Group (n = 116)	Non-HIP Group (n = 101)	p Value
Age, yrs	69 ± 8	68 ± 9	0.39
Male	90 (89%)	99 (85%)	0.41
Diabetes mellitus	35 (30%)	32 (32%)	0.81
Hypertension	79 (68%)	61 (60%)	0.24
Smoking	30 (26%)	30 (30%)	0.52
BMI, kg/m ²	24.2 ± 2.5	23.8 ± 3.7	0.35
Total cholesterol, mg/dl	198 ± 37	199 ± 40	0.84
HDL cholesterol, mg/dl	43 ± 11	48 ± 16	0.007
LDL cholesterol, mg/dl	136 ± 31	125 ± 29	0.008
hsCRP, mg/dl	2.1 (1.0, 3.6)	1.35 (0.5, 2.3)	0.001
IMT _{max} , mm	2.17 ± 1.1	1.67 ± 1.0	<0.001
Carotid artery stenosis, %	22.5 (15.0, 40.1)	20.5 (9.0, 40.9)	0.97
Medications			
Aspirin	110 (95%)	98 (97%)	0.41
Beta-blocker	67 (58%)	62 (61%)	0.59
Statin	71 (61%)	64 (63%)	0.74
ACEI or ARB	50 (43%)	47 (47%)	0.61
Multivessel CAD	55 (55%)	31 (31%)	0.01
LV dysfunction (EF <40%)	8 (7%)	6 (6%)	0.77
Previous MI	42 (36%)	21 (21%)	0.01

Values are mean ± SD, n (%), or median (first quartile, third quartile).

ACE = angiotensin-converting enzyme inhibitor; ARB = angiotensin II-receptor blocker; BMI = body mass index; CAD = coronary artery disease; EF = ejection fraction; HDL = high-density lipoprotein; HIP = high-intensity plaques; hsCRP = high-sensitivity C-reactive protein; IMT_{max} = maximum intima media thickness; LDL = low-density lipoprotein; LV = left ventricular; MI = myocardial infarction.

these data were subjected to Kaplan-Meier analysis, the presence of HIP was significantly associated with an increased probability of coronary events in patients with stable CAD ($p < 0.001$ by log-rank test) (Fig. 2). Univariate analysis of coronary risk factors, carotid ultrasound data, and MRI analysis showed that IMT_{max}, HIP, multivessel CAD, hsCRP, and previous MI were all significant predictors of clinical coronary events ($p < 0.05$) (Table 3). When these factors were further analyzed by a multivariate Cox regression analysis, the presence of HIP was found to be the most significant independent predictor of future coronary complications in patients with stable CAD (hazard ratio [HR]: 3.15, 95% confidence interval [CI]: 1.93 to 5.58, $p < 0.0001$) compared with IMT (HR: 1.62, 95% CI: 0.97 to 2.44, $p = 0.055$), hsCRP, previous MI, and multivessel CAD (Table 4). To further compare the presence of HIP to IMT, we used a cutoff value of >2.78 mm (i.e., the third quartile of IMT in the present study) to define elevated IMT and performed an alternative multivariate Cox regression analysis. When this cutoff value was used, IMT was significantly associated with cardiac events (HR: 1.79, 95% CI: 1.19 to 4.01, $p = 0.021$), but the presence of carotid HIP (HR: 3.10, 95% CI: 1.79 to 5.01, $p < 0.0001$) remained the strongest indicator of future coronary events.

Discussion

We wished to identify a technique to allow for the better stratification of patients at risk of coronary events, and we

hypothesized that the nature of atherosclerotic plaques throughout the vasculature could be associated with coronary plaque instability. As such, we used MPRAGE to examine the intensity of atherosclerotic plaques in the carotid arteries and followed up patients with both high- and low-intensity plaques for the subsequent development of coronary events. Our data suggest that the presence of HIP visualized by MPRAGE is a significant and independent predictor of future coronary events in patients with stable CAD. Furthermore, the presence of HIP was a stronger predictor of coronary events than increased carotid artery IMT. Thus, characterization of carotid plaques by MRI is clinically informative for risk stratification of patients with CAD.

Plaque instability and rupture were previously thought to be isolated events at a specific site within the vasculature, but recent observations suggest that plaque destabilization is a characteristic of some patients that occurs at multiple sites throughout systemic vascular beds (17,18). Thus, the presence of vulnerable carotid plaques may reflect a systemic problem with plaques within the coronary vasculature equally at risk to rupture and associated infarction. B-mode ultrasound of the carotid arteries can identify plaques and measure IMT, and both have been used as surrogate markers for cardiovascular disease. Although IMT and the presence of carotid plaques are highly related (19), the overall plaque area was a stronger predictor of future coronary events than IMT (20). Additionally, carotid plaque characteristics, for example, echolucency, predicted coronary plaque complexity, and the development of coronary complications in patients with CAD (2,21). While current data indicate that other radiologic measures may be better than IMT for coronary risk stratification, we elected to use IMT in this study because IMT is a more established technique, more widely available, and better validated in large populations (22).

In the present study, we used the MRI modality MPRAGE to characterize carotid plaques in patients with stable CAD. MPRAGE is a T1-weighted technique that highlights intraplaque components with short T1 signal with high signal intensity. It is thought that the lipid-rich necrotic cores of vulnerable plaques give rise to the observed short T1 signal (14,23–25). Alternatively, this may arise from intraplaque hemorrhage and thrombus formation (9,14,26,27). The presence of high-intensity signals suggestive of complicated plaques was associated with subsequent

Table 2 Summary of Coronary Events During Follow-Up Period in Patients With CAD

	HIP Group (n = 116)	Non-HIP Group (n = 101)	p Value
Composite endpoints	31	5	<0.001
Cardiac death	4	0	0.125
Nonfatal acute MI	4	1	0.375
Unstable angina	16	2	0.002
Hospitalization for recurrent angina	7	2	0.180

Abbreviations as in Table 1.

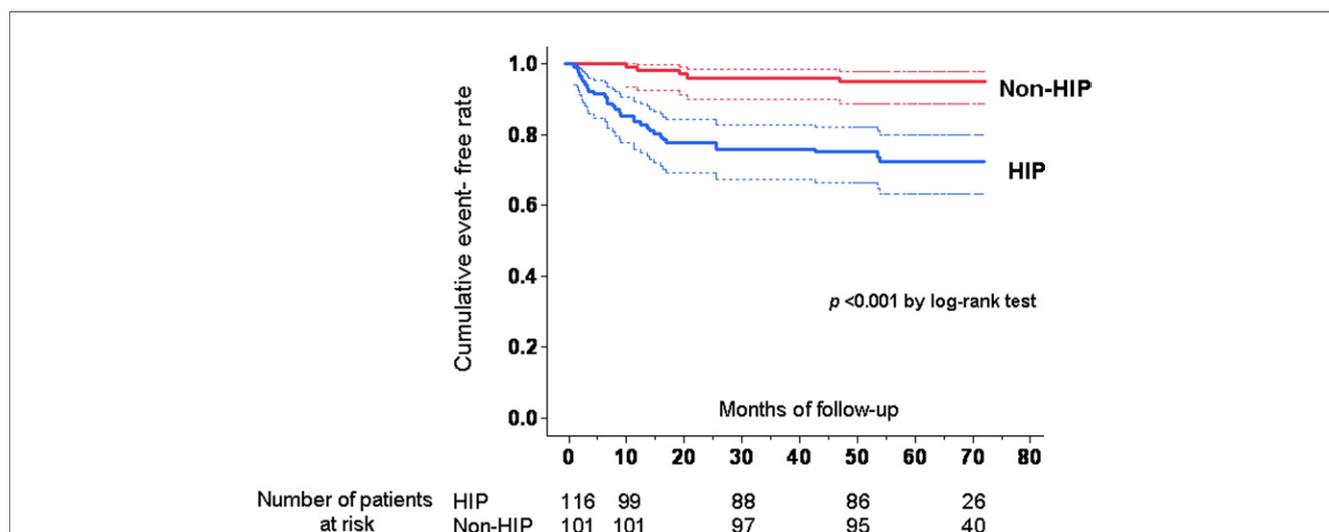


Figure 2 Kaplan-Meier Curves Comparing Probability of a Coronary Event

Kaplan-Meier curves comparing the probability of a coronary event occurring during the follow-up period of 72 months in 217 patients with stable coronary artery disease, grouped according to the presence or absence of high-intensity plaques (HIP). The **solid blue line** indicates patients with HIP ($n = 116$), and the **dotted blue lines** indicate confidence intervals. The **solid red line** indicates patients without HIP ($n = 101$), and the **dotted red lines** indicate confidence intervals.

ischemic cerebrovascular events, and this was recognized as an indicator of vulnerable carotid plaques (8,9). However, our current data greatly expand the significance of carotid HIP by showing that carotid HIP is a significant and independent predictor of future coronary events in patients with stable CAD. In fact, the presence of carotid HIP is a stronger indicator of future coronary events than increased IMT.

Recent advances in technology have allowed for the development of techniques that allow for the direct examination of coronary artery plaque composition, for example, intravascular ultrasound and angiography. However, these techniques are invasive and are not practical for use in routine screening for

the management and risk assessment of patients with CAD. Therefore, noninvasive imaging modalities capable of identifying patients harboring unstable coronary lesions are needed. Hence, the MRI-based evaluation of carotid plaques described here provides clinically important information on the vulnerability of coronary atherosclerotic plaques to rupture and correlates with future clinical outcome.

Inflammation plays important roles in atherogenesis and plaque rupture (15,28–31). A common inflammatory pathway linking carotid and coronary artery plaque activation has been proposed based on the observed high C-reactive protein levels seen in patients with CAD and echolucent carotid plaques (32). In this study, the plasma levels of hsCRP were significantly higher in the HIP group compared with the non-HIP group, and increased levels of hsCRP were independently associated with the presence of HIP. Increased hsCRP levels are an independent predictor of cardiovascular disease (33), and our results suggest that the presence of both MPRAGE-detected HIP and elevated hsCRP levels may indicate the presence of both vulnerable and inflammatory activated plaques.

Table 3 Univariate Analysis of Risk Factors for a Coronary Event in Patients With CAD

	Hazard Ratio	95% CI	p Value
Age, yrs	1.02	0.98–1.05	0.60
Male	1.71	0.72–3.32	0.29
Diabetes mellitus	1.68	0.88–4.41	0.15
Hypertension	0.89	0.47–1.61	0.71
Smoking	1.51	0.68–2.99	0.28
BMI, kg/m^2	0.98	0.79–1.01	0.18
Total cholesterol, mg/dl	0.86	0.71–1.00	0.17
HDL cholesterol, mg/dl	0.95	0.98–1.05	0.21
LDL cholesterol, mg/dl	1.12	0.98–1.05	0.35
hsCRP, mg/dl	1.41	1.02–1.51	0.03
IMT, mm	1.55	1.12–1.89	0.004
Multivessel CAD	2.18	1.21–6.12	0.001
LV dysfunction (EF <40%)	1.70	0.81–2.33	0.11
Previous MI	1.95	1.19–5.35	0.001
Presence of HIP	1.76	1.21–3.32	<0.001

CI = confidence interval; other abbreviations as in Table 1.

Table 4 Multivariate Cox Regression Analysis of Risk Factors for a Coronary Event

	β	SE	Hazard Ratio	p Value	95% CI
Presence of HIP	1.148	0.267	3.15	<0.0001	1.93–5.58
IMT, mm	0.480	0.191	1.62	0.055	0.97–2.44
hsCRP >3.0 mg/dl	0.334	0.195	1.40	0.099	0.94–2.02
Previous MI	0.189	0.195	1.21	0.330	0.83–1.77
Multivessel CAD	0.240	0.201	1.27	0.219	0.86–1.90

Abbreviations as in Tables 1 and 3.

Study limitations. This study was limited by the relatively small number of patients examined, and a few patients experienced a primary endpoint during the study. Hlatky et al. (34) reported that a greater number of outcome events are needed to provide adequate statistical power to fully evaluate whether a novel risk marker contributes additional prognostic information to an established set of risk factors in a multivariable model rather than simply indicating whether the new marker is a prognostic tool by itself. Therefore, while our data show that the presence of HIP is a risk factor for coronary events, the relative importance of HIP compared to other cardiac risk factors should be evaluated and confirmed in a larger prospective study. We enrolled patients with stable CAD with >50% stenosis, and most acute coronary events occur with low-grade or mild coronary stenosis. Additionally, we did not use a multicontrast approach including 3 basic contrast weightings (T1W, proton density, T2W). Use of these multicontrast approaches in conjunction with time-of-flight MRA has been shown to provide information regarding the thickness of the fibrous cap, the lipid-rich necrotic core, and intraplaque hemorrhage (12,35–37). The combination of MPRAGE with proton density and T2W techniques could further enhance imaging based predictions of coronary plaque vulnerability.

The risks of nephrogenic systemic fibrosis were less clearly understood during the study period in 2002 to 2005, and we did not exclude patients with a glomerular filtration rate <45 ml/min/1.73 m². The overall mean glomerular filtration rate of the study population was 78 ± 19 ml/min/1.73 m², and only 6 (2.7%) of the 217 patients had a GFR <45 ml/min/1.73 m². None of these patients had nephrogenic systemic fibrosis after administration of gadolinium.

Additionally, although we excluded 9 patients who had cardiac events in the first year of follow-up, the inclusion of these patients in the analyses did not affect the study results (data not shown). Finally, the number of clinical events in the study group was small, and follow-up was limited to 3 years. A more substantial, longer-term study with more patients is needed to clarify the short- and long-term prognostic roles of MRI as well as the role of MRI screening for high-risk asymptomatic patients.

Conclusions

The presence of HIP detected by MPRAGE in the carotid arteries predicts the development of future coronary complications in patients with stable CAD. Noninvasive evaluation of carotid plaques using MRI with MPRAGE is clinically informative in the risk stratification of CAD patients.

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Key Words: carotid artery ■ coronary artery disease ■ magnetic resonance imaging ■ prognosis.

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