Atherothrombosis is a systemic disease of the vessel wall that causes distinct clinical manifestations, depending on the affected circulatory bed and the characteristics of the individual lesions. These lesions may be quite heterogeneous. Thus, the clinical manifestations of atherothrombosis of the coronary arteries, of the arteries supplying the central nervous system, of the aorta, and of the peripheral circulation can be significantly different.

Disruption-prone plaques in the coronary arteries, the so-called “vulnerable plaques,” tend to have a thin fibrous cap (cap thickness ≈65 to 150 μm) and a large lipid core (American Heart Association [AHA] plaque type IV-Va). Acute coronary syndromes often result from disruption of a modestly stenotic vulnerable plaque, not visible by x-ray angiography, which results in a thrombotic complication (AHA plaque type VI). During its evolution, a type Va plaque may also become fibrotic (AHA plaque type Vc) or calcified (AHA plaque type Vb). In contrast to coronary artery vulnerable plaques characterized by high lipid content and a thin fibrous cap, high-risk plaques of the carotid arteries tend to be fibrotic and severely stenotic.

Imaging of Atherothrombotic Disease

Because there is striking heterogeneity in the composition of human atherothrombotic plaques, even within the same individual, reliable noninvasive imaging tools that can detect early atherothrombotic disease in the various regions and characterize the composition of the plaques are clinically desirable. Such imaging tools would improve our understanding of the pathophysiological mechanisms underlying atherothrombotic processes and allow us to better risk-stratify the disease. Additionally, such tools may permit optimal tailoring of treatment and allow direct monitoring of the vascular response.

Presently, a number of imaging modalities are employed to study atherosclerosis; most identify luminal diameter or stenosis, wall thickness, and plaque volume. Two noninvasive imaging modalities, computed tomography and MRI, have been introduced to the study of atherothrombosis. They allow identification of flow-limiting coronary stenoses, calcified plaques, imaging of the atherothrombotic lesions directly, measurement of atherosclerotic burden, and characterization of the plaque components. Together, by revealing the degree of stenosis and the plaque composition, they provide information that may predict cardiovascular risk, facilitate further study of atherothrombosis progression and its response to therapy, and provide for assessment of subclinical disease.

Computed Tomography

Methods

The cardiovascular system can be imaged with the use of two different computer tomography (CT) modalities: one employs nonmechanical movement of the x-ray source (ie, electron beam CT) and the other involves the motion of the x-ray source and table, combined with multiple detectors to acquire the data in spiral or helical fashion (ie, multidetector-row CT).

Electron-Beam CT

The necessity for very short image acquisition times to virtually freeze cardiac motion urged the development of a cardiac-dedicated CT system in 1982 on the basis of a nonmechanical movement of the x-ray source (ie, electron beam CT) and the other involves the motion of the x-ray source and table, combined with multiple detectors to acquire the data in spiral or helical fashion (ie, multidetector-row CT).

Multidetector-Row CT

Mechanical multidetector-row CT (MDCT) systems were introduced in 1998, and allow for scanning with one x-ray tube and 4 detector rows in a single gantry rotating twice per second around the patient. Continuous gantry rotation and table movement causes the projection data to be obtained along a spiral or helical path (Table 1).
Presently, the spatial resolution of MDCT is higher (0.6×0.6×1.0 mm³) than that of EBCT (0.8×0.8×2.5 mm³). However, continuous x-ray radiation during systole and diastole with MDCT means significantly higher exposure (9 mSv) than with EBCT (1.5 mSv). A technique designed to reduce the x-ray tube current of spiral MDCT during the cardiac cycle may lower the radiation exposure by 48% for males and 45% for females.⁴

Applications

Coronary Calcium

Atherosclerotic coronary calcifications²⁵ are most frequently found as lumps of calcium in advanced atherosclerotic lesions (AHA plaque type Vb) but may occur as small deposits of calcium in earlier lesions.⁵ Conventional plane chest x-ray, cine fluoroscopy, coronary angiography, ultrasound, and MRI can identify calcium in blood vessels; however, only EBCT and MDCT are able to accurately quantify the coronary calcium plaque burden.

EBCT for Coronary Calcium

Since the early 1990s, EBCT has been considered the “gold standard” for the assessment of calcified plaques.⁶⁷ ECG-triggered acquisition of the entire heart is performed with 3-mm contiguous slices progressing from the trunk of the pulmonary artery to the base of the heart during a single breathhold (∼30 to 40 s).

According to the American College of Cardiology/American Heart Association consensus document on coronary calcium,⁷ the clinical indications that may be considered are the detection of coronary calcium in patients with atypical chest pain, as well as the quantification and follow-up of the coronary calcium plaque load in asymptomatic patients with cardiovascular risk factors.⁸

Coronary artery calcium is assessed through the measurement of the number of pixels in the CT image with a density ≥130 Hounsfield units (HU). The total calcium score quantification scheme proposed by Agatston et al⁹ is the most widely used. Some limitations of the total calcium score include the low and variable reproducibility (14% to 51%).⁹ To overcome these limitations, the calcium volumetric score (CVS) was introduced.¹⁰ With the use of CVS, Callister et al¹⁰ illustrated the effect of lipid-lowering therapy on coronary calcification. However, there is no evidence that changes of coronary calcification correspond to changes in the cardiovascular events risk.⁷

A high coronary calcium score (CS) is a sensitive but not a specific marker for obstructive CAD.⁷ In many patients, coronary calcium is found even in the absence of any clinical coronary symptoms. Therefore, it has been suggested that coronary calcium may represent a preclinical stage of CAD. Whether coronary calcium is independent and superior to conventional risk factors as a predictor for future cardiac events is not yet well established.¹¹ Future randomized large prospective studies (eg, Prospective Army Coronary Calcium study¹²) may provide the definitive evidence of the predictive value of CS.

Multidetector-Row CT for Coronary Calcium

MDCT with retrospective ECG triggering acquires 3-mm slices with 1.5-mm overlap in a 15-s breathhold time (see Data Supplement figure). The CVS from MDCT correlates well with EBCT data in the same patient group.¹³ Compared with EBCT, MDCT demonstrated higher spatial resolution and signal-to-noise ratio; however, the longer exposure time (250 ms with MDCT versus 100 ms with EBCT), leads to motion artifacts.

The high spatial resolution and soft tissue delineation possible with contrast-enhanced (see later) multidetector-row coronary CT angiography (MD-CTA) may provide some information on noncalcified coronary artery lesions and noninvasively image the coronary artery wall.¹⁴ In a study by Schröder et al,¹⁵ soft, intermediate, and calcified plaques in the coronary arteries as defined by IVUS had a unique density, detected by contrast-enhanced MD-CTA (14±26 HU for soft plaques, 91±21 HU for intermediate plaques, and 419±194 HU for calcified plaques).¹³ In a preliminary study of heart specimen, we found that lipid-rich plaques had low density (50±12 HU), whereas fibrous plaques presented with higher density (89±31 HU) (Figures 1 and 2).¹⁶ Similar findings have been reported in carotid artery plaques.¹⁷

| TABLE 1. Comparison of EBCT and MDCT Imaging Parameters for Coronary Imaging |
|---------------------------------------------|-----------------------------|
| EBCT                                        | MDCT                        |
| X-ray source                               | 1 electron beam target      | 1 rotating x-ray tube |
| Detector                                   | 1 detector                  | 4 detector rows      |
| Scan geometry                              | Stationary target and detector | Rotating gantry |
| Temporal resolution                        | 100 ms                      | 250 ms              |
| Spatial resolution                         | 0.8 × 0.8 × 2.5 mm³         | 0.6 × 0.6 × 1.0 mm³ |
| Breathhold time                            | ∼40 s                       | ∼40 s               |
| Radiation exposure                         | 1.5 mSv                     | 9 mSv               |

Figure 1. MR and CT plaque characterization. Coronary artery calcified plaque. A, Cross-sectional ex-vivo T₂-weighted MR image of a human LAD with a small calcified lesion (arrow) and vessel wall thickening; B, Multislice CT image of the same lesion (arrow), showing the typical blooming effect of calcified lesions in CT images; C, Corresponding histopathologic section, calcium is washed out during the preparation process.
Further studies are essential to establish whether detection with contrast-enhanced MDCT of coronary lesions with noncalcified components identifies vulnerable plaques or patients that are at risk for developing coronary thrombosis and cardiac events.

### Coronary CT Angiography

#### Electron-Beam CT Angiography

Intravenous contrast was applied with electron-beam CT angiography (EB-CTA) for the assessment and quantification of coronary stenosis. EB-CTA is performed with 1.5- to 3-mm slices with a 1-mm slice overlap resulting in an ~40-s breathhold time. Homogenous enhancement of the coronary arteries is obtained with the intravenous administration of 120 mL of contrast media (400 mg iodine) injected at a flow rate of 3 mL/s. Initial results from the current studies are shown in Table 2.

It has also been shown\(^\text{18}\) that extensive calcifications may interfere with the detection of coronary artery stenoses, leading to false-negative results compared with selective coronary angiography. Small vessel diameters (<1.5 mm) were found to lead to false-positive stenosis findings.

#### Multidetector-Row CT Angiography

MD-CT angiography with retrospective ECG-gating is performed with 1.3-mm slices with 0.6-mm overlap (Figures 3 and 4). Similar to EB-CTA, after intravenous injection (3 mL/s) of a nonionic contrast medium (120 mL, 300 mg iodine) into the antecubital vein, the entire heart is scanned within a single breathhold time of ~40 s. The exposure time of 250 ms per slice requires lowering the heart rate to ≤60 bpm (eg, with the use of oral or intravenous β-blockers) to avoid cardiac motion image artifacts.\(^\text{19}\) However, in some patients, heart rates ≤60 bpm could not always be achieved at the expense of poor coronary artery visibility.\(^\text{20}\)

Two of the studies\(^\text{21,22}\) excluded ~30% of coronary segments mainly because of image degradation from cardiac motion. The image artifacts and the number of excluded coronary segments may be significantly reduced (to ~10%) by the use of β-blocker and careful patient selection.\(^\text{23}\) This allowed the imaging of the entire coronary tree within one breathhold.\(^\text{23}\) A summary of some of the coronary CTA studies by EBCT and MDCT is shown in Table 2.

### Possible Future Improvements

#### EBCT

Single-slice axial EBCT imaging with the use of nonspiral scanning diminishes the volume coverage of a single breathhold ECG-gated acquisition. Multiple stationary detectors may be needed for greater volume coverage and higher spatial resolution. New reconstruction algorithms may reduce the cone beam–induced artifacts\(^\text{24}\) and allow ECG-gated reconstruction from nonspiral continuous acquisition.

#### Multidetector-Row CT

The next generation MDCT scanner will allow for faster gantry rotation and simultaneous acquisition of >4 slices (eg, 16 slices). The breathhold time may decrease to ~20 s, thus reducing the necessary contrast media (eg, 60 mL) for sufficient enhancement of the coronary arteries. The temporal and spatial resolution may most likely increase to 200 ms and 0.8-mm slice thickness, respectively. These enhancements may help in the detection and grading of stenoses of the coronary arteries even in the presence of coronary calcium, and in quantification of calcified as well noncalcified lesions.

### Magnetic Resonance Imaging

#### Methods

During a magnetic resonance (MR) examination, the patient is subjected to a high local magnetic field, usually 1.5 Tesla, which aligns the protons in the body. These protons (or spins) are excited by a radiofrequency pulse and subsequently detected by receiver coils. Detected signals are influenced by the relaxation times (T1 and T2), proton density, motion and flow, molecular diffusion, magnetization transfer, changes in susceptibility, etc. Three additional magnetic fields (gradient fields) are applied during MRI; one selects the slice, and two encode spatial information. The timing of the excitation pulses and the successive magnetic field gradients determine the image contrast.\(^\text{25}\)

#### Multicontrast MR Plaque Imaging

High-resolution MR has emerged as the potential leading noninvasive in vivo imaging modality for atherosclerotic plaque characterization. MR differentiates plaque components on the basis of biophysical and biochemical parameters such as chemical composition and concentration, water content, physical state, molecular motion, or diffusion. MR provides imaging without ionizing radiation and can be repeated over time. In vivo MR plaque imaging and characterization have been performed utilizing a multicontrast approach with high-resolution black blood spin echo– and fast spin echo (FSE)–based MR sequences. The signal from the blood flow is rendered black through preparatory pulses (eg, radiofrequency spatial saturation or inversion recovery pulses) to better image the adjacent vessel wall.\(^\text{26}\) However, bright blood imaging (ie, 3D fast time of flight) can be employed in assessing fibrous cap thickness and morpholog-
Atherosclerotic plaque characterization by MR is generally based on the signal intensities and morphological appearance of the plaque on T1-weighted, proton density-weighted, and T2-weighted images as previously validated (see references in recent reviews by Fayad et al.\(^{3}\) and Yuan et al.\(^{28}\)).

**MR Coronary Angiography**

Coronary artery MR angiography (CMRA) is one of the most challenging areas of cardiovascular MR because of the size and topology of the arteries, as well as cardiac and respiratory motion. Since the publication of the first clinical results in 1993,\(^{29}\) CMRA has undergone numerous technical improvements and innovations.\(^{30}\) Three major groups or “generations” of coronary MRA techniques can be discerned. From all techniques available, 2D breathhold CMRA scans,\(^{21}\) 3D retrospective respiratory navigator-gated coronary MRA,\(^{32−39}\) and breathhold 3D CMRA\(^{40,41}\) have been evaluated clinically (Table 2 and Figure 5).

No specific MR techniques have emerged that can provide sensitivity and specificity for coronary lesion detection similar to those of traditional contrast coronary x-ray angiography. Moreover, compared with x-ray angiography, each of the techniques mentioned above suffer from limitations in temporal and spatial resolution, achieving spatial resolutions of \(\approx 1 \text{ mm}^3\) voxel size and temporal resolutions of 100 ms acquisition time per heartbeat, at best. Another limitation of

### TABLE 2. Sensitivity and Specificity of Coronary CT and MR Angiography Studies as Compared With Conventional Angiography (Stenoses>50%)

<table>
<thead>
<tr>
<th>Techniques</th>
<th>No. of Patients</th>
<th>No. of Patients, Vessels, or Segments Excluded (%)</th>
<th>Sensitivity, %</th>
<th>Specificity, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coronary EB-CTA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nakanishi et al 1997(^{62})</td>
<td>37</td>
<td>4 patients (11)</td>
<td>74</td>
<td>94</td>
</tr>
<tr>
<td>Achenbach et al 2000(^{63})</td>
<td>36</td>
<td>29 vessels (20)</td>
<td>92</td>
<td>94</td>
</tr>
<tr>
<td>Schmermund et al 1998(^{18})</td>
<td>28</td>
<td>93 segments (28)</td>
<td>82</td>
<td>88</td>
</tr>
<tr>
<td>Reddy et al 1998(^{34})</td>
<td>23</td>
<td>7 vessels (10)</td>
<td>88</td>
<td>63</td>
</tr>
<tr>
<td>Budoff et al 1999(^{65})</td>
<td>52</td>
<td>23 vessels (11)</td>
<td>78</td>
<td>91</td>
</tr>
<tr>
<td>Achenbach et al 1998(^{66})</td>
<td>125</td>
<td>124 vessels (25)</td>
<td>92</td>
<td>94</td>
</tr>
<tr>
<td>Coronary MD-CTA</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Niemann et al 2001(^{22})</td>
<td>35</td>
<td>64 segments (27)</td>
<td>83</td>
<td>90</td>
</tr>
<tr>
<td>Achenbach et al 2001(^{21})</td>
<td>64</td>
<td>82 vessels (32)</td>
<td>85</td>
<td>76</td>
</tr>
<tr>
<td>Knez et al 2001(^{23})</td>
<td>44</td>
<td>29 segments (6)</td>
<td>78</td>
<td>98</td>
</tr>
<tr>
<td>Vogl et al 2002(^{20})</td>
<td>64</td>
<td>38 segments (19) for HR&lt;60 bpm</td>
<td>75</td>
<td>99</td>
</tr>
<tr>
<td>Coronary MRA first generation, 2D breathhold</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Manning et al 1993(^{29})</td>
<td>39</td>
<td>9 vessels (6)</td>
<td>90</td>
<td>92</td>
</tr>
<tr>
<td>Post et al 1997(^{71})</td>
<td>35</td>
<td>15 vessels (11)</td>
<td>63</td>
<td>89</td>
</tr>
<tr>
<td>Coronary MRA second generation, 3D retrospective respiratory gating</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Post et al 1996(^{12})</td>
<td>20</td>
<td>3 vessels (4)</td>
<td>38</td>
<td>95</td>
</tr>
<tr>
<td>Mueller et al 1997(^{33})</td>
<td>35</td>
<td>35 segments (14)</td>
<td>83</td>
<td>94</td>
</tr>
<tr>
<td>Kessler et al 1997(^{77})</td>
<td>73</td>
<td>219 segments (48)</td>
<td>65</td>
<td>88</td>
</tr>
<tr>
<td>Van Geuns et al 1999(^{14})</td>
<td>32</td>
<td>52 segments (26)</td>
<td>50</td>
<td>91</td>
</tr>
<tr>
<td>Sandstede et al 1999(^{35})</td>
<td>30</td>
<td>7 patients (23)</td>
<td>81</td>
<td>89</td>
</tr>
<tr>
<td>Huber et al 1998(^{38})</td>
<td>20</td>
<td>45 segments (31)</td>
<td>79</td>
<td>54</td>
</tr>
<tr>
<td>Sardanelli et al 2000(^{36})</td>
<td>42</td>
<td>39 segments (14)</td>
<td>82</td>
<td>89</td>
</tr>
<tr>
<td>Gonsior et al 2001(^{168})</td>
<td>20</td>
<td>45 segments (31)</td>
<td>79</td>
<td>54</td>
</tr>
<tr>
<td>Nikolaou et al 2001(^{37})</td>
<td>40</td>
<td>75 segments (27)</td>
<td>72</td>
<td>60</td>
</tr>
<tr>
<td>3D prospective respiratory gating</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lethimonnier 1999(^{10})</td>
<td>20</td>
<td>3 patients (15)</td>
<td>65</td>
<td>93</td>
</tr>
<tr>
<td>Kim et al 2001(^{14})</td>
<td>109</td>
<td>123 segments (16)</td>
<td>93</td>
<td>42</td>
</tr>
<tr>
<td>Coronary MRA third generation, 3D breathhold</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Van Geuns et al 2000, non contrast-enhanced(^{4}^{4})</td>
<td>38</td>
<td>85 segments (31)</td>
<td>68</td>
<td>97</td>
</tr>
<tr>
<td>Regenfus et al 2000, contrast-enhanced(^{43})</td>
<td>50</td>
<td>82 segments (23)</td>
<td>86</td>
<td>91</td>
</tr>
</tbody>
</table>

EB-CTA indicates electron beam CT angiography; MD-CTA, multidetector-row CT angiography.
CMRA, compared with x-ray angiography and CTA, is the necessity of data acquisition over several heartbeats, which can lead to motion artifacts. A more detailed review of the current status of CMRA application can be found in Duerinckx.30

**Applications**

**MR Plaque Imaging**

**Noncoronary Plaques With MRI**

MR has been used to study atherosclerotic plaques in human carotid,42 aortic,26 and coronary43 arterial disease. In vivo images of advanced lesions in carotid arteries have been obtained from patients referred for endarterectomy.42,44 The superficial location and relative absence of motion in carotid arteries presents less of a technical challenge for imaging than the aorta or coronary arteries. Short T2 components were quantified in vivo before surgery and correlated with values obtained in vitro after surgery.42 Some of the MR studies of carotid arterial plaques include the imaging and characterization of atherosclerotic plaques,42,44 the quantification of plaque size,43 and the detection of fibrous cap “integrity.”27 Typically the images are acquired with a resolution of 0.25×0.25×2.0 to 0.4×0.4×3.0 mm3 by use of a carotid phased-array coil to improve signal-to-noise ratio and image resolution.

In vivo, black-blood MR atherosclerotic plaque characterization of the human aorta has been reported recently by Fayad et al,26 who assessed thoracic aorta plaque composition and size with the use of T1-weighted, T2-weighted, and proton density–weighted images. The acquired images had a resolution of 0.8×0.8×5.0 mm3 with a phased-array coil. Rapid high-resolution imaging was performed with an FSE sequence in conjunction with velocity-selective flow suppression preparatory pulses. Matched cross-sectional aortic imaging with MR and transesophageal echocardiography showed a strong correlation for plaque composition and mean maximum plaque thickness. An asymptomatic patient with complex carotid, aortic arch, and descending aorta plaque as detected by MR is shown in Figure 6. Contrast-enhanced MRA with the use of gadolinium-based contrast agents may provide additional information for plaque characterization by identifying neovascularization in the atherosclerotic plaque and potentially improve the differentiation between necrotic core and fibrous tissue.46 Furthermore, other nonspecific and specific contrast agents may facilitate accurate plaque constituent characterization and the identification of specific molecular and biological activity.47,48

**Coronary Plaques With MRI**

Preliminary studies in a pig model showed that the difficulties of coronary wall imaging are the result of a combination of cardiac and respiratory motion artifacts, nonlinear course, small size, and location.49 Fayad et al extended the black-blood MR methods used in the human carotid artery and aorta...
to the imaging of the coronary arterial lumen and wall.\textsuperscript{43} The method was validated in swine coronary lesions induced by balloon angioplasty.\textsuperscript{49}

High-resolution black-blood MR of both normal and atherosclerotic human coronary arteries was performed for direct assessment of coronary wall thickness and the visualization of focal atherosclerotic plaque in the wall. The difference in maximum wall thickness between the normal subjects and patients (\(\geq 40\%\) stenosis) was statistically significant. Figure 7 shows in vivo MR coronary plaque images from 3 patients. The coronary MR plaque imaging study by Fayad et al\textsuperscript{43} was performed during breathholding to minimize respiratory motion with a resolution of \(0.46 \times 0.46 \times 2.0\) mm\(^3\). To alleviate the need for the patient to hold his or her breath, Botnar et al\textsuperscript{50} have combined the black-blood FSE method and a real-time navigator for respiratory gating and real-time slice position correction. A near isotropic spatial resolution (\(0.7 \times 0.7 \times 1\) mm\(^3\)) was achieved with the use of a 2D local inversion and black-blood preparatory pulses.\textsuperscript{50} This method provided a quick way to image a long segment of the coronary artery wall and may be useful for rapid coronary plaque burden measurements. Future studies need to address these possibilities.

### In Vivo Monitoring of Progression and Regression of Plaques With MRI

As shown in animal experimental studies,\textsuperscript{51,52} MR is a powerful tool to serially and noninvasively investigate the progression and regression of atherosclerotic lesions in vivo. In asymptomatic, untreated, hypercholesterolemic patients with carotid and aortic atherosclerosis, Corti et al\textsuperscript{53} have shown that MR can be used to measure the efficacy of lipid-lowering therapy (statins). Atherosclerotic plaques were assessed with MR at different times after lipid-lowering therapy. Significant regression of atherosclerotic lesions was observed. Despite the early and expected hypolipidemic effect of the statins, changes in the vessel wall were observed for 12 months. As with previous experimental studies, there was a decrease in the vessel wall area and no alteration in the lumen area after 12 months.\textsuperscript{51,52} Recently, a case-controlled study demonstrated substantially reduced carotid plaque lipid content (but no change in overall lesion area) in patients treated for 10 years with an aggressive lipid-lowering regimen compared with untreated controls.\textsuperscript{54}

### Coronary MR Angiography

Magnetic resonance offers several advantages for coronary imaging.\textsuperscript{30} MR does not use ionizing radiation and does not necessarily require the injection of a contrast agent. Several MR techniques have been proposed for the detection of coronary stenosis with MR, but no large population study has been presented.

A large multicenter study that uses a standardized 3D prospective respiratory navigator approach has been presented.\textsuperscript{39} The study population consisted of 109 subjects from 7 US and European centers who were scheduled to undergo their first elective x-ray coronary angiography for suspected CAD. The mean CMRA time was 74 minutes. The evaluation was limited to the proximal 3 to 5 cm of the major coronary arteries. Of the 759 coronary segments available for analysis, 636 (84%) could be interpretable by CMRA. In these segments (\(\geq 50\%\) stenosis), 78 of 94 stenoses (83%) were detected by CMRA. Overall, CMRA has an accuracy rate of 72% (95% confidence interval, 63% to 81%) in diagnosing CAD. From this study we can reach the following 3 conclusions: (1) If the goal is to identify those without any coronary disease and save them from coronary x-ray angiography, CMRA will make x-ray angiography unnecessary in 20% (however, 18% of this group (4% of total) will have their single-vessel disease undiagnosed) (2) if the goal is to identify those without left main or 3-vessel disease and save them from coronary x-ray angiography, CMRA will make x-ray angiography unnecessary in 69% of patients (in a similar cohort); and (3) most patients with isolated distal coronary disease will be missed by CMRA. It is necessary to

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**Figure 5.** A 64-year-old patient with stenosis in proximal and middle segments of left anterior descending artery. Conventional coronary angiography (A) reveals stenosis in proximal and middle segment of left anterior descending artery. Curved multiplanar reconstruction of MR coronary angiography (B) shows left anterior descending artery with signal loss at a proximal stenosis (arrow) and at a stenosis in middle segment (arrowhead). Modified from Huber et al.\textsuperscript{38}

**Figure 6.** Complex carotid and aortic plaques detected in a 71-year-old female patient by use of high-resolution in vivo MRI. A, Left carotid artery plaque (arrow). B, Aortic arch plaque (arrow). C, Descending aortic plaque (arrow).
define the groups of patients who may benefit from this CMRA technique and to evaluate thoroughly the new and evolving imaging techniques in the appropriate clinical settings.55

Today, established clinical applications of CMRA include the evaluation of the patency of coronary artery bypass grafts and the imaging of anomalous coronary arteries.30

Possible Future Improvements

**MR Plaque Imaging**

Thinner slices, such as those obtained with 3D acquisition techniques, could further improve artery wall imaging.50 Additional MR techniques, such as water diffusion weighting,56 magnetization transfer weighting,28 steady-state free precession (SSFP) sequences,57 contrast enhancement,46 and molecular imaging47,48 may provide complementary structural information and allow more detailed plaque characterization. New and improved blood suppression methods50 are necessary for accurate plaque imaging, especially in the carotid artery bifurcation.

**MR Coronary Angiography**

Various new CMRA techniques await further clinical trials to determine their effectiveness. For example, Stuber et al58 combined a dual-inversion 3D FSE imaging sequence with real-time navigator technology for high-resolution, free-breathing black-blood CMRA. Deshpande et al59 evaluated the effectiveness of an extracellular contrast agent with the use of breathhold segmented echoplanar imaging and found substantial improvement in the delineation of the coronary arteries. Segmented 3D SSFP was also described as a promising technique with substantially increased signal-to-noise ratio and contrast-to-noise ratio for coronary artery imaging compared with a conventional gradient-echo technique with the same imaging time.60 New intravascular contrast agents may provide the long-awaited boost for reliable magnetic resonance coronary angiography. Initial studies in subjects have shown promising results.61

**CT and MR Imaging Combination**

Cross-sectional modalities MRI and CT offer more information than just displays of the patient coronary vessel lumen. The advantage of MDCT is the potentially complete assessment of the entire coronary artery tree within a very short scan time, and MRI offers excellent soft tissue contrast. However, because of the limited scan range and long examination time for MRI, MDCT may first be used to localize suspicious CAD lesions in the coronary arteries. With the knowledge of the problematic site in the coronary arteries from MDCT, this may be followed by MRI for further lesion assessment.

Improved CT and MR imaging of the coronaries may in the future allow for better noninvasive evaluation of atherosclerotic plaques. For example, a pilot study is being conducted (Figure 8) for the characterization of plaques with the use of CT and MR in high-risk asymptomatic patients. This study involves CT, CS measurements, contrast-enhanced CT for plaque burden and stenosis assessment, and multicontrast MR plaque characterization for a detailed analysis and follow-up of the composition of coronary atherosclerotic lesions. The flow chart in Figure 8 is not a clinical recommendation or guideline for practice but serves for a better understanding of

![Figure 7. In vivo MR black-blood cross-sectional images of human coronary arteries demonstrating a plaque presumably with deposition of fat (arrow, A) a concentric fibrotic lesion (B) in the left anterior descending artery, and an ectatic, but atherosclerotic, right coronary artery (C). RV indicates right ventricle; LV, left ventricle. Modified from Fayad et al.43](image)

<table>
<thead>
<tr>
<th>Sequence</th>
<th>CT (HU)</th>
<th>T1W</th>
<th>PDW</th>
<th>T2W</th>
<th>TOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recent thrombus</td>
<td>20</td>
<td>+</td>
<td>+/−</td>
<td>−</td>
<td>+/−</td>
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<tr>
<td>Lipid</td>
<td>50</td>
<td>+</td>
<td>−</td>
<td>+/−</td>
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<tr>
<td>Fibrous</td>
<td>100</td>
<td>+/−</td>
<td>+</td>
<td>+/− to +</td>
<td>+/− to −</td>
</tr>
<tr>
<td>Calcium</td>
<td>&gt;300</td>
<td>−</td>
<td>−</td>
<td>−</td>
<td>−</td>
</tr>
</tbody>
</table>

SI indicates signal intensity; T1W, T1-weighted; T2W, T2-weighted; and PDW, proton-density weighted.

*SI relative to adjacent muscle.
†Vessel contrast enhancement.
+, Hyperintense.
+/-, Isointense.
−, Hypointense.

**TABLE 3. Contrast at CT and MR Imaging of Main Components of Atherosclerotic Plaque**
the utility of the noninvasive combined CT and MR imaging modalities for future therapeutic strategies. Further studies are needed to test the concepts we are presenting here.

**Conclusions**

CT and MR imaging are emerging as the most promising complementary imaging modalities for coronary atherosclerotic disease detection. They identify flow-limiting coronary stenoses and calcified plaques, directly image the atherosclerotic lesions, measure atherosclerotic burden, and characterize the plaque components. Together, they provide unique information that may predict cardiovascular risk, facilitate further study of the mechanisms of atherosclerosis progression and its response to therapy, and allow for assessment of subclinical disease. However, published studies with relatively small numbers of patients were conducted independently with either CT or MR. These results should be validated in large-scale clinical trials before CT and MR are implemented clinically, outside of research settings, especially for atherosclerotic disease screening. This type of clinical investigation is needed to define the technical requirements for optimal imaging, develop accurate image analysis methods, outline criteria for interpretation, delineate the clinical indications for which CT and MR imaging together should be used as an adjunct to conventional imaging, and address the issue of cost-effectiveness.

Finally, imaging may address the high-risk plaque, as described in this paper, but it does not take into account the blood hypercoagulable state or markers of inflammation. Therefore, one of the ultimate goals for the clinicians is the identification of the high-risk patient through a combination of strategies such as assessment of conventional risk factors, blood markers, and imaging.62–69

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**References**


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