Cardiac MRI in Ischemic Heart Disease

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Considerable progress has been made in cardiac magnetic resonance imaging (MRI). Cine MRI is recognized as the most accurate method for evaluating ventricular function. Late gadolinium-enhanced MRI can clearly delineate subendocardial infarction, and the assessment of transmural extent of infarction on MRI is widely useful for predicting myocardial viability. Stress myocardial perfusion MRI allows for detection of subendocardial myocardial ischemia, and the diagnostic accuracy of stress perfusion MRI is superior to stress perfusion single-photon emission computed tomography in patients with multivessel coronary artery disease (CAD). In recent years, image quality, volume coverage, acquisition speed and arterial contrast of 3-dimensional coronary magnetic resonance angiography (MRA) have been substantially improved with use of steady-state free precession sequences and parallel imaging techniques, permitting the acquisition of high-quality, whole-heart coronary MRA within a reasonably short imaging time. It is now widely recognized that cardiac MRI has tremendous potential for the evaluation of ischemic heart disease. However, cardiac MRI is technically complicated and its use in clinical practice is relatively limited. With further improvements in education and training, as well as standardization of appropriate study protocols, cardiac MRI will play a central role in managing patients with CAD. (Circ J 2009; 73: 1577–1588)

Key Words: Coronary artery disease; Ischemic heart disease; Myocardial infarction; Perfusion

The first ECG-gated magnetic resonance (MR) images of the heart were acquired more than 25 years ago, and MR imaging (MRI) was initially used to evaluate the morphology and motion of the heart. With developments of late gadolinium-enhanced (LGE) MRI and myocardial perfusion MRI, the application of MRI in ischemic heart disease (IHD) has been considerably expanded in the past 10 years. Because MRI has high spatial resolution and excellent image contrast, subendocardial infarction and myocardial ischemia can be clearly visualized. In addition, MRI does not expose the patient to ionizing radiation nor require the administration of iodinated contrast medium, which is potentially nephrotoxic. Coronary MR angiography (MRA) is rapidly evolving and has emerged as a possible alternative to multidetector-row computed tomography (MDCT) for noninvasive visualization of coronary artery disease (CAD). In this review, we describe recent advances of cardiac MRI and coronary MRA, and demonstrate the usefulness of MRI for the diagnosis and risk stratification in patients with IHD.

Assessment of Cardiac Function

Breath-hold cine MRI with steady-state free precession (SSFP) sequence and segmented k-space acquisition has become the standard method of evaluating the morphology and function of the heart. Right ventricular (RV) function, as well as left ventricular (LV) function and mass, can be accurately determined with cine MRI.1,2 Compared with cardiac MDCT, excellent delineation of blood and myocardium can be obtained on SSFP cine MRI without contrast administration.3,4 With the use of cardiac multichannel receiver coils and parallel imaging techniques, such as sensitivity encoding (SENSE), the imaging time of SSFP cine MRI has been considerably shortened. Compared with echocardiography, MRI is not influenced by lung air, allowing the acquisition of high-quality cine MRI of the entire heart in any desired double oblique imaging planes, even in patients with pulmonary emphysema. Cine MRI is less operator-dependent and shows high inter-study reproducibility in the assessment of ventricular volumes and mass. This allows a considerable reduction in the patient numbers required to prove a hypothesis in research studies, offering a potential saving in costs.5

High-dose dobutamine stress echo (40 μg·kg⁻¹·min⁻¹) has become a well-established method for the diagnosis of myocardial ischemia. However, dobutamine stress echo has several disadvantages, including operator dependency and poor endocardial delineation in the basal lateral and inferior segments in a certain percentage of patients. Cine MRI allows noninvasive assessment of altered regional wall motion during dobutamine stress in all segments of the LV, with high spatial and temporal resolution. The respective sensitivity and specificity of high-dose dobutamine stress cine MRI were 83% and 83% by Hundley et al.,6 86% and 86% by Nagel et al.,7 89% and 75% by Jahneke et al.,8 and 78% and 88% by Paetsch et al.9 for the detection of significant CAD. A recent meta-analysis of dobutamine stress cine MRI from 14 datasets demonstrated a sensitivity of 83% and a specificity of 86% by patient-based analysis.10 Dysfunctional but viable myocardium may have functional recovery if revascularized in patients with hibernating...
myocardium in chronic ischemia, and with time in patients with stunned myocardium in acute ischemia. MR assessment of myocardial viability can be achieved with either low-dose dobutamine stress cine MRI or LGE MRI, which will be explained later. Low-dose (10 μg·kg<sup>-1</sup>·min<sup>-1</sup>) dobutamine stress MRI is useful for predicting functional recovery of dysfunctional LV segments in patients with myocardial infarction (MI).<sup>11</sup> Several studies have demonstrated that low-dose dobutamine stress cine MRI gives a more accurate prediction of functional recovery when compared with LGE MRI in patients with MI.<sup>12,13</sup>

Although cine MRI demonstrates excellent delineation of the endocardial and epicardial borders, the contractile pattern within the LV wall can not be evaluated with the ordinary cine MR approach. Myocardial tagging MRI uses radiofrequency preparation pulses that label the myocardium as a dark grid or series of dark lines.<sup>14,15</sup> Deformation of the grid or lines caused by myocardial contraction is then analyzed. Regional wall motion abnormalities can be more accurately assessed with strain analysis of tagging cine MRI in comparison with conventional cine MRI.<sup>16</sup> The tagging MRI approach is also useful for accurate and objective assessment of altered regional myocardial function during dobutamine stress in patients with myocardial ischemia,<sup>17</sup> and in those with ischemic cardiomyopathies.<sup>18</sup> The first paper on MR tagging, published 20 years ago, was by Zerhouni et al.<sup>15</sup> Since then, many investigators have demonstrated that MR tagging is an (extremely) useful tool for studying regional myocardial contraction. However, analysis of tagging cine MRI remains a complex and time-consuming process, limiting its widespread adoption in patients with IHD.

Strain-encoded (SENC) MRI and displacement encoding with stimulated echoes (DENSE) MRI are new approaches that can quantify myocardial strain. Conventional tagging MRI labels the myocardium with tag lines that are perpendicular to the imaging plane. In contrast, SENC MRI uses tag surfaces that are parallel to the MR imaging plane, and acquires 2 or more images with different phase encodings in a direction perpendicular to the imaging plane. Longitudinal strain can be calculated from SENC MRI with simple, fast post-processing; for example, myocardial longitudinal strain can be assessed by acquiring SENC MRI on short-axis imaging planes, and circumferential strain can be computed from DENSE MRI acquired on long-axis imaging planes. DENSE MRI is a new technique for quantitative motion tracking of the myocardium.<sup>22</sup> DENSE allows direct measurement of the displacement of myocardial tissue during the cardiac cycle. The advantages of the DENSE approach include higher spatial resolution of strain mapping compared with tagging MRI, and direct extraction of tissue displacement. Circumferential strain and radial strain can be computed from DENSE MRI acquired on short-axis imaging planes. Because signal intensity on the phase subtraction images of DENSE MRI directly correlates with displacement of myocardial tissue, strain analysis of DENSE MRI can be completed within several seconds without manual interaction.

Figure 1. Displacement encoded imaging with stimulated echoes (DENSE) in a patient with acute inferior myocardial infarction. On DENSE strain maps (A), both circumferential strain (Left, blue) and radial strain (Right, red) are impaired in the inferior wall. Late gadolinium-enhanced (LGE) MR images in the long-axis view (B) and short-axis view (C) show the infarction in the inferior wall. Rest-perfusion magnetic resonance imaging (MRI) (D) demonstrates a myocardial perfusion abnormality in the inferior wall (D). Transmural myocardial edema in the inferior wall is detected on the black-blood T2-weighted MRI (E). The area of myocardium with abnormal strain on DENSE is larger than the area with myocardial edema on black-blood T2 weighted MRI, but similar to the area with abnormal blood flow on rest-perfusion MRI (Analysis of strain on DENSE MRI can be completed within several seconds without manual interaction).
Detection of Myocardial Ischemia

Despite the recent progress in the noninvasive visualization of the coronary artery tree using MDCT, stress myocardial perfusion imaging is important for the assessment of patients with IHD, because morphological narrowing of the coronary artery does not correlate well with the functional significance of CAD. Myocardial perfusion has been evaluated by single-photon emission computed tomography (SPECT), but patients are exposed to radiation and the diagnostic accuracy is sometimes limited by relatively low spatial resolution and artifacts from photon scatter and tissue attenuation. First-pass contrast-enhanced MRI of the myocardium with pharmacological stress has emerged as a noninvasive method that enables accurate assessment of myocardial ischemia caused by flow-limiting stenosis. ECG-gated dynamic MR images were acquired to monitor first-pass dynamics of the contrast medium through the LV myocardium. Ischemic myocardium with reduced myocardial blood flow is visualized as an area exhibiting slower enhancement compared with normal myocardium on the stress perfusion MRI. The spatial resolution of MRI is substantially higher than that of SPECT, allowing visualization of subendocardial ischemia. Resting myocardial blood flow remains normal until diameter narrowing of the coronary artery exceeds 90%. Therefore, exercise or pharmacological stress that augments myocardial blood flow is necessary to detect ischemia by perfusion imaging. Because of the difficulty in inducing sufficient exercise stress while the patients is supine within the MR magnet, pharmacological stress with a vasodilator agent, such as adenosine, ATP or dipyridamole, is used. These vasodilator agents relax the tonus of smooth muscle cells around the arteriolar wall and increase myocardial blood flow by factor of 3–5 in subjects without significant CAD or microvascular disease.

Myocardial perfusion MRI is acquired with a T1-weighted dynamic MR imaging sequence (Figure 2). Gadolinium contrast medium at a dose of 0.05–0.1 mmol/kg is rapidly injected in the antecubital vein, followed by a saline flush. There are several important requirements for stress perfusion MRI, including (1) high spatial resolution, (2) high temporal resolution, (3) good contrast between normal myocardium and ischemic myocardium and (4) reduced artifact. A saturation recovery preparation pulse is used to generate T1 contrast on the myocardial perfusion MRI. For image data acquisition of myocardial perfusion MRI, fast gradient-echo sequence,24 gradient-echo sequence with echo-planar readouts,25 and SSFP sequence26 have been used. Each image acquisition approach has advantages and disadvantages. We use SSFP perfusion MRI sequences at 1.5 tesla (T) because that there is a higher signal-to-noise ratio compared with other acquisition methods. It should be noted that SSFP myocardial perfusion MRI is relatively sensitive to cardiac motion during image acquisition. In order to minimize motion artifacts, we acquire SSFP perfusion MR images at end-systole and mid-diastole when cardiac motion is minimal. The SSFP sequence is sensitive to susceptibility effect and a high concentration of gadolinium contrast medium in the LV chamber may cause a dark-rim artifact along the endocardial border, so a lower dose (0.05 mmol/kg) is preferable.

The diagnostic accuracy of stress perfusion MRI for the detection of significant CAD has been investigated in many single-center studies in the past decade. Schwitter et al used a gradient-echo sequence with echo-planar readouts and reported a sensitivity of 91% and a specificity of 94% when stress ammonium positron emission tomography was used as a reference method, and a sensitivity of 87% and a specificity of 85% for detecting significant CAD on quantitative coronary angiography (CAG).27 Nagel et al28 used a gradient-echo sequence with echo-planar readouts and determined the myocardial perfusion reserve (MPR) index. In their study, stress myocardial perfusion MRI had a sensitivity of 88%, a specificity of 90% and an accuracy of 89%. In a recent meta-analysis study by Nandalur et al that analyzed 1,183 patients in 14 single-center studies with an averaged CAD prevalence of 57.4%, the averaged sensitivity and specificity of stress perfusion MRI was 91% and 81%,10

There are several multicenter studies that have evaluated the diagnostic performance of stress myocardial perfusion MRI at 1.5 T. In a multicenter dose-ranging study by Wolff et al,29 the highest diagnostic performance was observed at a low dose of gadolinium (0.05 mmol/kg; area under the receiver-operating characteristic (ROC) curve 0.90±0.04). Sensitivity, specificity, and accuracy of stress perfusion MRI at this dose were 93%, 75%, and 85%, respectively.
A recent multicenter study performed in Japan, stress perfusion MRI resulted in an area under the ROC curve of 0.92 for observer 1 and 0.84 for observer 2, with respective sensitivity and specificity of 89% and 79% for observer 1, and 83% and 71% for observer 2.30

Atherosclerosis occurs in multiple vascular areas and significant CAD has been found in 31%–53% of patients with aortic aneurysms.31 The use of routine CAG in all patients with aortic disease may increase unnecessary risk and costs, and interpretation of coronary CT angiography is often difficult in patients with aortic disease because of the heavy coronary artery calcification. One study has demonstrated that stress perfusion MRI combined with LGE MRI is useful for noninvasive detection of CAD in patients prior to elective repair of aortic aneurysms, with sensitivity, specificity and accuracy of 88%, 87% and 88%, respectively.31

Stress myocardial perfusion SPECT has been widely used for the assessment of myocardial ischemia. However, it is acknowledged that its diagnostic accuracy is limited in patients with multivessel CAD because of equilibration of ischemia. The high spatial resolution of myocardial perfusion MRI enables detection of diffuse subendocardial ischemia in patients with multivessel disease. In our single-center studies, the diagnostic accuracy of stress perfusion MRI was superior to that of stress SPECT.32,33 The area under the ROC curve for detection of significant CAD was 0.84–0.86 for stress perfusion MRI, significantly higher than that of stress perfusion SPECT (0.72–0.79).32 In a recent multicenter, multivendor prospective trial by Schwitter et al, the diagnostic performance of stress perfusion MRI (area under the ROC curve 0.86±0.06) was better than that of stress perfusion SPECT (0.67±0.05, P=0.003), particularly in patients with 2- and 3-vessel disease.34

The high spatial resolution of myocardial perfusion MRI is important not only for the detection of subendocardial ischemia, but also for the reduction of the dark-rim artifact along the endocardial border. K-space and time SENSE (k-t SENSE) is a new, fast imaging technique that can accelerate dynamic MR acquisition by a factor of up to 5. The improved acquisition speed achieved by k-t SENSE can be used for improving the spatial resolution of myocardial perfusion MRI. Plein et al demonstrated the feasibility of high-spatial-resolution perfusion MRI at 1.5T accelerated by k-t SENSE in both volunteers35 and patients with CAD.36 They found that k-t SENSE-accelerated perfusion MRI accurately detects myocardial ischemia in single- and multivessel CAD with reduced artifact because of the improved in-plane spatial resolution. ROC analysis yielded an area under the ROC curve for detection of coronary stenosis of 0.85 for all patients, and 0.82 and 0.87 for patients with single- and multivessel disease, respectively.36

There is an increasing interest in 3T cardiac MRI, because high-field MRI has an improved signal-to-noise ratio and T1-contrast compared with 1.5T.37–39 Gebker et al demonstrated that myocardial perfusion MRI using a saturation–recovery gradient-echo sequence at 3T has an accuracy of 84% for depicting hemodynamically significant coronary artery stenoses in patients with suspected and known CAD.37 Cheng et al showed that 3T myocardial perfusion MRI is superior to 1.5T for the prediction of single- and multivessel CAD, with a higher diagnostic accuracy (90% vs 82%), sensitivity (98% vs 90%) and specificity (76% vs 67%) compared with 1.5T. Plein et al recently demonstrated the feasibility of k-t SENSE-accelerated high-spatial-resolution perfusion MRI at 3T.39 When compared with standard-resolution 3T perfusion MRI using SENSE, k-t SENSE perfusion MRI at 3T demonstrated improved spatial resolution and reduced artifacts.

Myocardial perfusion MRI can be evaluated by visual analysis, semi-quantitative analysis or quantitative analysis. Quantitative analysis of myocardial blood flow and MPR provides a more objective evaluation of myocardial ischemia and microvascular disease.40–46 One of the difficulties in achieving absolute quantification of myocardial blood flow is that the MR signal from the LV blood pool is no longer proportional to the gadolinium concentration during the first pass. Dual-bolus administration of gadolinium contrast medium was proposed as an approach that enables quantitative assessment of myocardial perfusion while maintaining excellent contrast enhancement in the myocardium.45 There are several different approaches for absolute quantification of myocardial blood flow from myocardial perfusion MRI, including a model-independent deconvolution method,44 and a Patlak plot analysis method recently established by Ichihara et al.45 In order to validate the quantitative analysis of MPR using this approach, Kurita et al determined the relationship between the MPR by Patlak plot analysis and coronary flow velocity reserve (CFR) by Doppler flow wire in patients with CAD, and found that a MPR <2.0 by MR Patlak analysis has a sensitivity of 87.5% and a specificity of 90.0% in predicting a reduction of CFR (<2.0) by Doppler wire.47

In patients with known or suspected CAD, stress myocardial perfusion imaging is important not only for detecting or excluding flow-limiting CAD but also for evaluating prognosis. Jahnke et al reported that in patients with known or suspected CAD, myocardial ischemia detected by stress cardiac MRI is useful for identifying patients at high risk for subsequent cardiac death or nonfatal MI. The 3-year event-free survival was 99.2% for patients with normal stress MRI and 83.5% for those with abnormal stress MRI, and stress MRI provided important incremental information over and above the clinical risk factors and resting wall motion abnormalities. Bodi et al reported that dipyridamole stress myocardial perfusion MRI can predict clinical events over the subsequent months in patients with known or suspected IHD.49 In another study by Bodi et al,50 the prognostic and therapeutic implications of dipyridamole stress perfusion MRI were investigated in patients with CAD. Patients with severe ischemia who exhibited a stress induced perfusion deficit and wall motion abnormality on MRI were at the highest risk and were benefited most from revascularization.

MRI of MI

In recent years, LGE MRI has become widely used for the detection and characterization of MI and myocardial fibrosis. LGE MRI has 3 major features: direct correlation with histopathological infarction, high spatial resolution that delineates subendocardial infarction, and high contrast between normal and infarcted myocardium. The extent of abnormal enhancement on LGE MRI linearly correlates with the TTC area of MI in both acute and chronic MI in animal models.53 High spatial resolution enables detection of small, subendocardial infarction, which is difficult to detect with radionuclide imaging. In an animal study using histopathology specimens as the reference, LGE MRI identified 92% of the segments with a subendocardial infarction,
**Figure 3.** A patient with a subendocardial myocardial infarction. Steady-state free precession cine MR images in the diastolic (A) and systolic (B) phases demonstrate no regional wall motion abnormality. Late gadolinium-enhanced MR images in the short-axis (C) and long-axis (D) views show a subendocardial infarction in the anteroseptal wall (arrows). Myocardial viability is preserved in the infarcted area.

**Figure 4.** A patient with a transmural myocardial infarction. Steady-state free precession cine MR images in the diastolic (A) and systolic (B) phases reveal akinesis and myocardial wall thinning in the anteroseptal wall (arrows). Late gadolinium-enhanced MR images in the short-axis (C) and long-axis (D) views demonstrate the transmural infarction in the anteroseptal wall and apex (arrows). Myocardial viability is not preserved in the infarcted area.
whereas SPECT detected only 28%. The high contrast between normal and infarcted myocardium achieved with inversion recovery (IR) preparation is another important advantage of LGE MRI compared with contrast-enhanced MDCT.

LGE MRI is acquired by IR prepared imaging sequences after administration of gadolinium contrast medium. A standard method of acquiring late-enhanced MRI is to obtain IR prepared segmented k-space gradient-echo MR images 10–15 min after intravenous injection of gadolinium contrast medium at a dose of 0.15–0.2 mmol/kg. However, in several countries, including Japan, only single-dose gadolinium injection (0.1 mmol/kg) is approved for contrast-enhanced cardiac MRI. With single-dose gadolinium injection, the contrast between normal myocardium and infarction often becomes insufficient if images are acquired after 10 min. Therefore, it is recommended to start acquisition of LGE MRI in less than 10 min when the gadolinium dose is $<0.15$ mmol/kg. For accurate assessment of MI and fibrosis, careful adjustment of the inversion time (TI) to null the signal from normal myocardium is important because the contrast between normal and infarcted myocardium is determined by the TI. A look-locker pulse sequence that acquires multiple images with different TI times during a single breath-hold is useful to find the optimal TI for LGE MRI. A phase-sensitive image reconstruction method is another approach that can simplify the choice of TI. LGE MR images have been acquired with 2-dimensional (2D) IR gradient-echo sequences. The conventional 2D gradient-echo approach provides excellent delineation of myocardial fibrosis in cardiomyopathies, as well as MI, but it is a time-consuming procedure and repeated breath-holds are required to cover the entire heart. A 3-dimensional (3D) IR gradient sequence allows rapid acquisition of 3D images that cover the LV within 1 breath hold. Free-breathing acquisition of 3D IR gradient-echo images is also feasible using respiratory gating with navigator echo.

LGE MRI is now widely used for the assessment of myocardial viability in patients with acute or chronic MI. In a study evaluating patients with chronic MI, functional recovery after revascularization inversely correlated with the transmural extent of enhancement on LGE MRI. Segments with a transmural extent of MI $>50\%$ had a low likelihood of recovery of systolic thickening after revascularization. LGE MRI is useful to differentiate dysfunctional but viable myocardium from infarction in patients with acute MI. In a study by Kitagawa et al, the diagnostic accuracy of LGE MRI and that of rest thallium-201 (Tl-201) SPECT were compared in patients after acute MI. The sensitivity, specificity and accuracy of LGE MRI in predicting of functional recovery were significantly higher than those of Tl-201 SPECT. It should be noted that the transmural extent of MI is significantly reduced from the acute to the chronic state, because of involution of necrotic tissue. Therefore, myocardial segments with 50–75% transmural extent of gadolinium enhancement in the acute state may exhibit functional recovery.

LGE MRI is useful for classifying patients with heart failure in relation to the presence or absence of underlying CAD. McCrohon et al evaluated the value of LGE MRI...
for differentiating dilated cardiomyopathy (DCM) from LV dysfunction caused by CAD. All patients with LV dysfunction and CAD had subendocardial or transmural enhancement. In DCM patients, 59% had no late enhancement and 28% showed mid-wall fibrosis. In another study by Soriano et al, 81% of the patients with CAD on X-ray CAG had subendocardial or transmural enhancement, whereas only 9% of the angiographically negative group demonstrated late gadolinium enhancement. LGE MRI should be more widely used in patients with heart failure for differentiating ischemic cardiomyopathy from nonischemic DCM.

Recently, the prognostic importance of LGE MRI has been gaining attention. Kwong et al studied patients with suspected CAD who had no prior MI, and found that the presence and extent of myocardial scar detected by LGE MRI was a strong predictor of major cardiac events and cardiac death. Myocardial scar is more frequent than expected. In a population-based study in Sweden that randomly selected 70-year-old subjects in the community, unrecognized MI was detected by LGE MRI in 19.8% of the subjects without a history of MI. LGE MRI can detect small subendocardial old MI, which is very difficult to detect with other methods such as blood test, electrocardiography, echocardiography and radionuclide study. In particular, silent MI is prevalent among diabetic patients. A recent study using LGE MRI revealed a high prevalence (28%) of myocardial scar in diabetic patients without clinical evidence of MI. In addition, diabetic patients without clinical evidence of MI, but with MR evidence of infarction, had significantly worse event-free survival compared with the patients without MR evidence of MI (P=0.001). These recent findings indicate that screening of unrecognized myocardial scarring with contrast-enhanced MRI will have an important role for detecting patients at high risk of future cardiovascular events.

In patients with chronic MI, a standardized cardiac MR protocol consists of cine MRI and LGE MRI. It is required to take cine MRI, black-blood T2-weighted MRI, rest perfusion MRI and LGE MRI for the adequate assessment of acute MI (Figure 5). Black blood T2-weighted MRI can detect myocardial edema in patients with acute MI. Because both acute and chronic MI demonstrate late gadolinium enhancement, T2-weighted MRI is useful for distinguishing acute infarction from chronic infarction. In acute MI, the myocardium that exhibits edema, but no late gadolinium enhancement, corresponds to the “area at risk”.

Early revascularization of the infarct-related artery and restoration of myocardial tissue blood flow are the objectives of coronary intervention in patients with acute MI. However, there are still patents who demonstrate LV dysfunction despite successful revascularization therapy. MRI is useful for tissue characterization of reperfused MI. Microvascular obstruction is revealed as an area of perfusion defect on rest perfusion MRI, indicating occlusion of capillaries at the myocardial tissue level (Figure 6). On LGE MRI, microvascular obstruction is shown as a non-enhanced area, typically in the subendocardial layer, sur-
rounded by an area with late gadolinium enhancement. The presence of microvascular obstruction is usually associated with poor functional recovery of regional myocardial dysfunction.

**MRA of Coronary Arteries**

X-ray CAG has been widely used for the assessment of CAD, but invasive CAG is associated with a small but non-negligible risk, and a considerable number of patients who undergo diagnostic X-ray CAG are found to not have significant CAD. Contrast-enhanced MDCT is now widely used as a noninvasive method of ruling out significant CAD. Coronary MRA has several potential advantages in comparison with MDCT. Firstly, it does not expose the patients to ionizing radiation. Because the cancer risk from radiation exposure is substantially higher in children than in adults, coronary MRA is ideally suited for the assessment of anomalous coronary arteries in children and young adults, and for noninvasive detection and size measurement of coronary artery aneurysms in patients with Kawasaki disease. Secondly, no contrast injection is necessary to obtain coronary MRA, at least when using 1.5 T MR imagers. Thirdly, the lumen of the coronary artery can be visualized in patients with heavy coronary artery calcification. However, MR imaging of the coronary arteries has been technically challenging because of their small diameter of and complex motion caused by both cardiac contraction and respiration. Despite recent advances in fast MR imaging techniques, the acquisition speed of 3D MRA is considerably slower than that of 64-slice MDCT, making it very difficult to obtain high resolution 3D MRA images covering the entire coronary artery tree within a single breath-hold.

With developments and refinements of respiratory gating with navigator echoes, SSFP sequence, parallel imaging technique with multi-coils, and improved strategies for k-space sampling, such as radial k-space sampling, the image quality and acquisition speed of coronary MRA have improved. It is now feasible to use free-breathing coronary MRA for screening luminal narrowing of the coronary arteries in patients with suspected CAD. In a multicenter study that evaluated the diagnostic accuracy of free-breathing 3D gradient-echo coronary MRA, the sensitivity and specificity were 93% and 42%, respectively, for detecting patients with significant CAD, and 100% and 85%, respectively, for predicting patients with left main CAD and 3-vessel disease. With the target volume method used in that multicenter study, however, coronary MRA was time-consuming because only a portion of all the coronary arteries was imaged with double-oblique 3D acquisition. Whole-heart coronary MRA using a free-breathing, 3D SSFP sequence was introduced as a method that can visualize all 3 major coronary arteries with a single axial 3D acquisition. Whole-heart coronary MRA becoming quite simple, eliminating the time-consuming 3-point planning required for the targeted double oblique approach. In an initial feasibility study in patients with suspected CAD, acquisition of whole-heart coronary MRA was successful in 34 (87.2%) of 39 patients, with an average acquisition duration of 13.8±3.8 min. Data acquisition using a subject-specific acquisition window is important to reduce motion blurring of the coronary artery during whole-heart coronary MRA. An ECG trigger delay time and an interval of minimal motion of the right coronary artery
artery are determined on cine MRI for subsequent whole-heart coronary MRA acquisition. In a single-center study by Jahnke et al.,85 32 patients with suspected CAD were studied. Whole-heart coronary MRA demonstrated a moderate sensitivity of 78% and a high specificity of 91% for the detection of significant CAD on a vessel-based analysis. Another single-center study assessing 131 subjects also reported a moderate sensitivity of 78% and a high specificity of 96% for whole-heart coronary MRA.86 Whole-heart coronary MRA in those previous studies was acquired with 5-channel cardiac coils and SENSE factor of 2. Because of the relatively long MRA acquisition time, typically ranging from 10 to 15 min, coronary MRA was not successfully completed in patients who had an unstable breathing pattern or drift of the diaphragm position during scanning. Imaging time for whole-heart coronary MRA can be considerably shortened by using 32-channel cardiac coils and a high SENSE factor of 4. In our preliminary study using 32-channel coils, whole-heart coronary MRA was successfully acquired in 62 of 62 subjects (100%) with an average MRA imaging time of 6.1±2.6 (Figure 7).

An improved signal-to-noise ratio of coronary MRA can be expected with a magnetic field strength of 3 T. Stuber et al initially demonstrated the feasibility of coronary MRA at 3 T in healthy volunteers.87 Sommer et al evaluated the image quality and accuracy of 3 T coronary MRA in patients with suspected CAD.88 They used ECG-gated, free-breathing 3D gradient-echo MRA without administering gadolinium contrast medium. Although the contrast-to-noise ratio increased from 21.8% to 23.5% at 3 T compared with 1.5 T, 3 T gradient-echo coronary MRA without contrast did not result in significant improvements in the overall image quality and diagnostic accuracy. It should be noted that the SSFP at 1.5 T can provide excellent blood contrast without the use of gadolinium contrast medium. Because of increased B1 field inhomogeneity and radio-frequency energy deposition at high field strengths, the gradient-echo sequence has better tolerance at 3 T. A slow injection of high dose MR contrast medium is useful to achieve a high contrast-to-noise ratio on 3 T whole-heart coronary MRA.89

In a recent study by Yang et al.,90 the diagnostic performance of 3 T contrast-enhanced whole-heart coronary MRA was evaluated in 69 patients with suspected CAD. They reported a high sensitivity and moderate specificity of 94.1% and 82.1%, respectively, for the detection of patients with >50% stenoses in the coronary arteries. As previously mentioned, 3 T whole-heart coronary MRA with an IR prepared gradient-echo sequence relies on double-dose infusion of a high relaxative contrast medium. Use of contrast media increases cost, and is associated with potential side-effects. Noncontrast enhanced, 1.5T SSFP, whole-heart coronary MRA and contrast-enhanced 3T whole-heart MRA are not competing modalities and will have different clinical indications in the future.

Conclusions

Cardiac MR sequences for cine MRI, perfusion MRI and LGE MRI have already matured. Cardiac MRI is now recognized as a modality that can provide a precise and highly reproducible assessment of morphology, function, blood flow and tissue characterization in patients with IHD. However, cardiac MRI is still technically complicated, and its capabilities and clinical applications are less familiar to cardiologists at this point in time. Standardized MR protocols of cardiac MR studies, education and training for
adequate acquisition and interpretation of cardiac MR images, and effort to improve reimbursement of cardiac MRI are required to expand the use of MRI in IHD.

MRI of the coronary arteries is still rapidly evolving. Whole-heart coronary MRA allows for noninvasive detection of significant coronary artery stenosis with high sensitivity and moderate specificity, either by using the 1.5T SSFP approach or the 3T contrast-enhanced approach. It should be noted that the current whole-heart coronary MRA is optimized for assessing luminal stenoses in the coronary arteries, and does not provide information regarding the presence or characteristics of atherosclerotic plaque in the coronary arterial wall. Although further studies are definitely required, noninvasive MR imaging techniques that can detect plaque hemorrhage and the lipid-rich necrotic core in the coronary arterial wall seem to have great diagnostic and prognostic potential (Figure 8).

References


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