# Coronary CT versus MR Angiography: The Role of MR Angiography[1]

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Coronary artery disease (CAD) is the most frequent cause of death in many developed countries (1), and there is a strong need for a noninvasive test that can reliably be used to delineate CAD without the use of ionizing radiation. Coronary magnetic resonance (MR) angiography has a history of nearly 20 years, and considerable technical advances have been made during this period (2). Despite high initial expectations, however, coronary MR angiography is not frequently used for the assessment of CAD. In an expert consensus document on "appropriate" indications for cardiac computed tomography (CT) and MR imaging published in 2006 (3), coronary CT is recommended as an "adequate" imaging method for ruling out significant CAD in patients who have chest pain symptoms, with intermediate pretest probability of CAD. In contrast, coronary MR angiography is categorized as an "inappropriate" method for excluding significant CAD in the same subject group. Coronary CT angiography is superior to coronary MR angiography in terms of spatial resolution and study success rate. Long image times and operator dependency have limited the widespread use of coronary MR angiography. Because of these limitations, most experts and clinical guidelines supported the use of coronary MR angiography only for the assessment of anomalous coronary arteries and coronary artery aneurysms in patients with Kawasaki disease.

As the number of cardiac CT examinations rapidly grows in many hospitals, however, the value of coronary MR angiography for the assessment of CAD without radiation exposure has been rediscovered, stimulating the effort to close the gap between CT and MR angiography. By using newer techniques, such as high-field-strength MR, 32-channel cardiac coils, and high parallel imaging factors, the diagnostic accuracy, imaging time, and study success rate of coronary MR angiography have steadily improved during the past few years (4,5). Assessments of stress-induced ischemia and myocardial viability are critically important to make optimal therapeutic decisions and to improve prognosis of the patients. The capability to perform comprehensive assessments of cardiac function, perfusion, and viability, as well as coronary imaging, is a major strength of cardiac MR imaging (6,7). The purpose of this article is to explain the pros and cons of coronary MR angiography in comparison with CT and to give a perspective of MR imaging for the assessments of the lumina and the vessel walls of coronary arteries.

## Technical Considerations

Coronary MR angiography has several important advantages over cardiac CT. First, coronary MR angiography does not expose the patient to ionizing radiation. Coronary MR angiography is suited for assessing coronary arteries in children and young adults, because the cancer risk from radiation exposure is higher in children (8). Second, the lumen of the coronary artery can be assessed even in a segment with heavily calcified plaque. In a study with the use of dual-source CT, heavy calcification was found to be associated with a significant reduction in the diagnostic accuracy (9). Coronary MR angiography may provide better diagnostic performance for the detection of CAD in patients with high calcium scores (10). Third, the coronary arteries may be visualized without the need for exogenous contrast agents (Fig 1). The high T2/T1 ratio of the blood acts as an intrinsic contrast medium for SSFP coronary MR angiography (11,12). Fourth, the temporal resolution of free-breathing coronary MR angiography can be flexibly determined by using imaging parameters, while the temporal resolution of cardiac CT is predominantly determined by using the gantry rotation speed.

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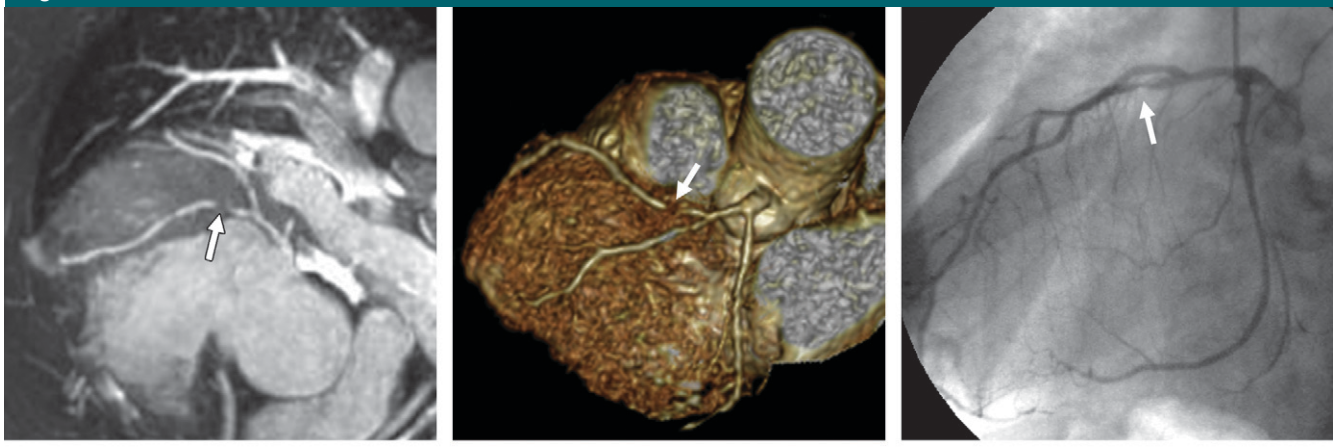
See also the article by Dewey in this issue.

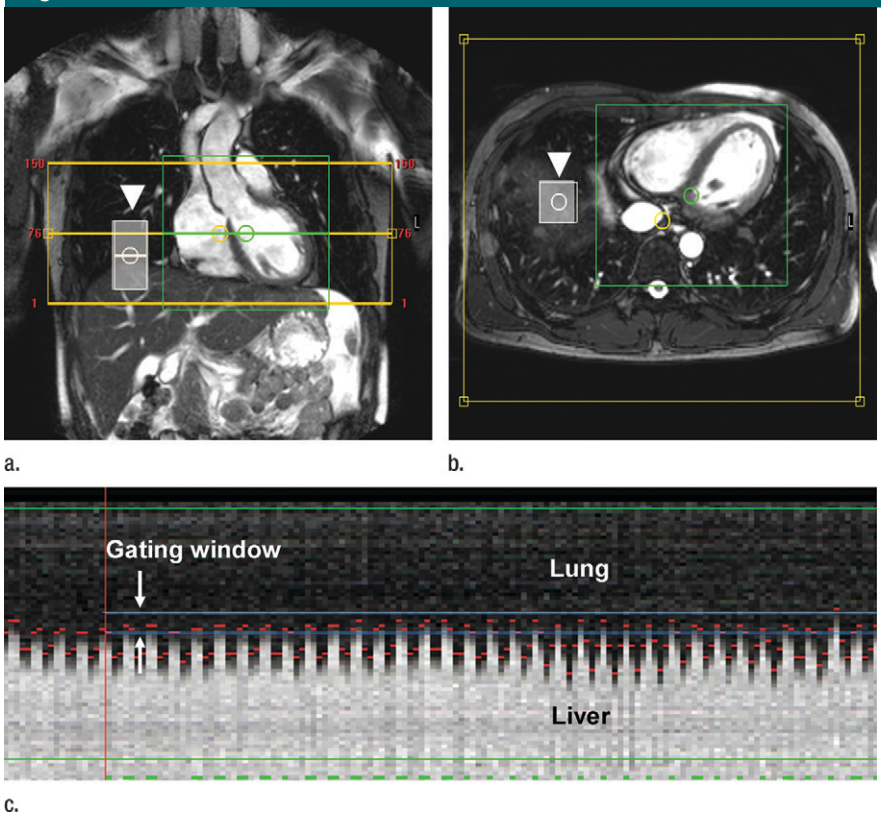
**Figure 1**



a. b. c.

**Figure 1:** Nonenhanced 1.5-T whole-heart coronary MR angiography in a 60-year-old man who presented with chest pain on effort. Images were acquired by using a steady-state free precession (SSFP) sequence with T2 preparation, spectral presaturation inversion-recovery fat saturation (repetition time msec/echo time msec, 4.6/2.3; flip angle, 90°; sensitivity encoding [SENSE] factor, four; field of view, 280 × 280 × 120 mm; acquisition matrices, 256 × 256 × 80; reconstruction matrices, 512 × 512 × 160). **(a)** Thin-section maximum intensity projection (MIP) image and **(b)** volume-rendered image depict coronary artery stenosis in the left anterior descending artery (arrow). Good agreement was observed between coronary MR angiograms and **(c)** conventional coronary angiogram.

**Figure 2**




a. b. c.

**Figure 2:** Acquisition of whole-heart coronary MR angiograms by using navigator echo in a healthy volunteer. For respiratory gating, a selective two-dimensional radiofrequency pulse was used to excite a column of tissue perpendicular to the right lung-diaphragm interface (arrowhead), as shown on the **(a)** coronal and **(b)** axial scout images. The position of the lung-liver interface was monitored in real time, as shown on **c**. If the lung-liver interface position is inside the gating window, image data in that cardiac cycle are accepted for reconstruction. Electrocardiographically gated data acquisition is continued until all data in k-space are collected. Yellow box = imaging acquisition volume, green box = shim volume, blue lines = respiratory gating window, green lines = cardiac cycle accepted for reconstruction, red line = lung-liver interface position.

Lower spatial resolution and lengthy imaging time are major limitations of coronary MR angiography in comparison with coronary CT. Coronary MR angiographic data are typically acquired with an acquisition resolution of 1–1.5 mm and an imaging time ranging from 5 to 15 minutes by using free-breathing, respiratory-gated sequences (4,13,14) (Fig 2). The gap between MR angiography and CT in terms of acquisition speed is hard to overcome, because coronary CT images can be acquired in less than several seconds at higher spatial resolution with recent CT scanners. Breath-hold three-dimensional (3D) coronary MR angiography has advantages in terms of time efficiency compared with free-breathing 3D coronary MR angiography

**Figure 3**

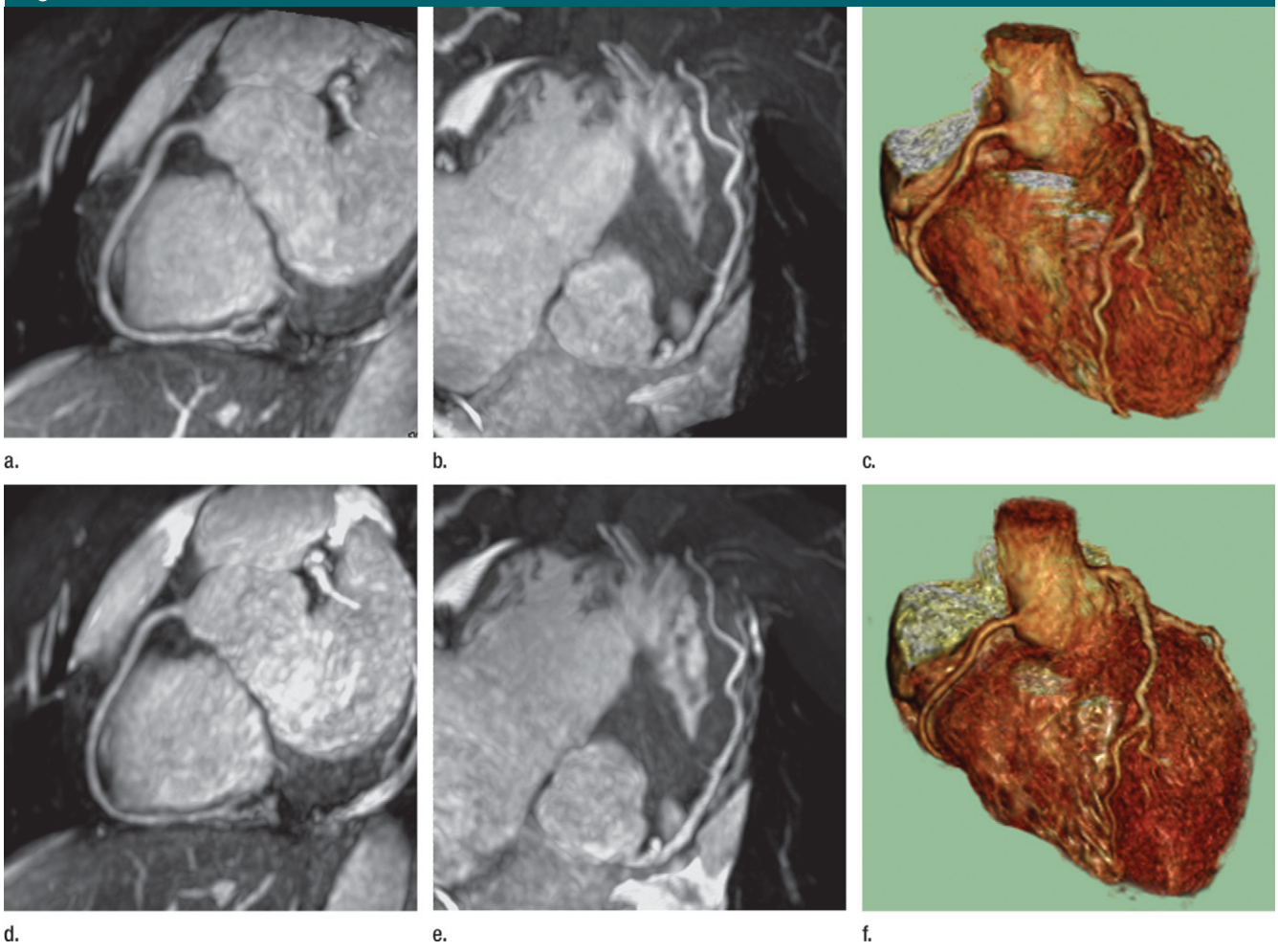



**Figure 3:** Nonenhanced 1.5-T whole-heart coronary MR angiography in a healthy 30-year-old male volunteer performed with **(a–c)** five-channel cardiac coils and **(d–f)** 32-channel cardiac coils. **(a, b, d, e)** Thin-section MIP images and **(c, f)** volume-rendered images are shown. The acquisition time of MR angiography was 12 minutes with five-channel coils and 6 minutes with 32-channel coils. Despite the reduced acquisition time, image quality of MR angiograms acquired with 32-channel coils seems to be at least equivalent to that of MR angiograms acquired with five-channel coils.

(15,16). However, the short imaging time is achieved at the expense of spatial resolution and 3D volume coverage.

MR of the coronary arteries has been steadily evolving for the past several years. Whole-heart coronary MR angiography has commonly been performed with five-channel cardiac coils and a parallel imaging factor of two (13,14,17–19). Because of the relatively long MR angiographic acquisition time, coronary MR angiography was not successfully completed in a certain percentage of patients who demonstrated drift of the diaphragm position during imaging. The imaging time of coronary MR angiography can be substantially reduced by using 32-channel cardiac coils (20) and a higher parallel imaging factor of four (Fig 3). This reduction in imaging time may lead to an improved study success rate with whole-heart coronary MR angiography. High-field-strength 3.0-T systems have been shown to improve the signal-to-noise ratio of coronary MR angiography (21,22). The results in a recent single-center study suggested that the diagnostic performance of 3.0-T contrast material–enhanced whole-heart coronary MR angiography approaches the diagnostic performance of 64-section CT (4).

## Patient Preparation, Examination, and Interpretation

Patients with permanent cardiac pacemakers or implantable cardioverter-defibrillators are generally excluded from coronary MR angiographic studies. Intracoronary stents are not contraindications of MR imaging (23), although MR angiography does not allow direct visualization of in-stent restenosis. A prosthetic heart valve, annuloplasty ring, and sternal wires are considered to be safe, while artifacts may disturb delineation of the coronary arteries near the metal. Most pulse sequences used for coronary MR angiography have an

"arrhythmia rejection" capability that can eliminate artifacts caused by occasional premature contractions. However, continuous variation of the heart rate during imaging in patients with atrial fibrillation often results in suboptimal quality of coronary MR angiograms or failure of acquisition.

For coronary CT angiography, oral or intravenous administration of β-blockers is frequently required in patients with a heart rate of greater than 65 beats per minute to reduce motion artifacts on coronary CT angiograms (24,25). In contrast, the temporal resolution of coronary MR angiography is not constrained by MR hardware and can be modified for each subject by the MR operator (26,27). In a recent study (19) in which the researchers evaluated the diagnostic performance of whole-heart coronary MR angiography in patients with a heart rate of less than 70 beats per minute and in patients with a heart rate of greater than 70 beats per minute, the sensitivity and specificity did not significantly differ between the two groups, indicating that diagnostic coronary MR angiography can be performed without the use of β-blockers even in patients with a high heart rate. However, administration of β-blockers may be helpful to reduce the imaging time of free-breathing coronary MR angiography, because the prolonged diastolic rest period of coronary arteries at a lower heart rate allows the acquisition of an increased number of k-space lines per cardiac cycle. Sublingual nitrates induce endothelium-independent vasodilation in the epicardial coronary arteries (28) and help to improve the signal-to-noise ratio of coronary MR angiography (29).

Coronary MR angiography was initially performed with a target-volume method (30,31). With this approach, repeated acquisitions were obtained of double oblique 3D volumes for left main and left anterior descending, left circumflex, and right coronary arteries. The target-volume method was highly operator dependent and time-consuming because the position and course of each major coronary artery needed to be determined before the MR angiographic acquisition. Whole-heart coronary MR angiography performed by using a free-breathing 3D SSFP sequence was introduced as a method that could provide visualization of all three major coronary arteries with a single axial 3D acquisition (13,14,17). The target-volume approach has been largely replaced by the whole-heart coronary MR angiographic approach today, because of the simplicity of this approach in prescribing image location and because of the reduction in total imaging time.

At 1.5 T, excellent blood contrast can be obtained by using SSFP MR angiographic sequences without injection of gadolinium-based contrast medium. However, at 3.0 T, administration of MR contrast medium is highly effective to achieve high blood contrast, because the gradient-echo sequence instead of the SSFP sequence has a better clinical performance owing to increased magnetic field inhomogeneity and radiofrequency energy deposition at a high field strength (32,33). A short inversion time inversion-recovery method has been most often used for contrast-enhanced coronary MR angiography (32). With the short inversion time inversion-recovery approach, both fat signal and myocardial signal are strongly attenuated at inversion time of approximately 200 msec, while the magnetization of blood has already recovered by shortening T1 relaxation time of the blood with MR contrast medium. Intravascular MR contrast medium remains in the vascular space for the prolonged period of time, which is suited for free-breathing coronary MR angiography (34–36). However, intravascular MR contrast media are not yet approved for the evaluation of CAD in most countries. An alternative approach is to use conventional extracellular gadolinium-based contrast agents that quickly extravasate from blood in the vascular space to the extracellular space. Consequently, contrast-enhanced MR angiographic data need to be collected during first-pass (37) or continuous slow infusion of gadolinium-based contrast agents with extracelluar distribution (4,32).

Coronary MR angiography has been assessed on source 3D images, multiplanar reformation images, thin MIP images, or volume-rendered images. On CT angiograms, the visualization of a coronary arterial lumen with thin-section MIP can be degraded by the presence of heavily calcified plaque. In contrast, luminal narrowing of the coronary artery can be visualized by using thin-section MIP on coronary MR angiograms, even in patients with calcified coronary plaques. In addition, blood signal in the epicardial veins can be suppressed with a T2 preparation pulse, allowing differentiation between coronary arteries and veins. The presence or absence of significant CAD on coronary MR angiograms has been qualitatively assessed in previous studies (19,30), but methods for quantitative analysis of luminal narrowing of the coronary artery have not yet been established. It should be noted that surrounding tissue with a long T2 relaxation time, such as a pericardial effusion or blood in the ventricular chambers, appears bright on SSFP MR angiograms. Automated 3D segmentation of the coronary arterial tree from nonenhanced whole-heart MR angiograms is more difficult in comparison with contrast-enhanced CT, owing to the presence of high-intensity pericardial effusion with MR in proximity to the coronary arteries and lower arterial image contrast compared with enhancement with contrast-enhanced CT.

## Indications for Coronary MR Angiography

Anomalous origin of the coronary artery is an important cause of chest pain and sudden cardiac death. Among various types of anomalous coronary arteries, the coronary arteries that pass between the aorta and the pulmonary artery have a potential to impair myocardial perfusion and can cause sudden death. Coronary MR angiography has high sensitivity and specificity in the detection of anomalous coronary arteries and is useful in delineating proximal courses of the vessels (38,39). Anomalous coronary arteries can be assessed by using contrast-enhanced CT as well. However, the MR angiographic approach provides equivalent diagnostic information in regard to the presence of anomalous coronary arteries and their proximal courses without exposing the

**Figure 4**

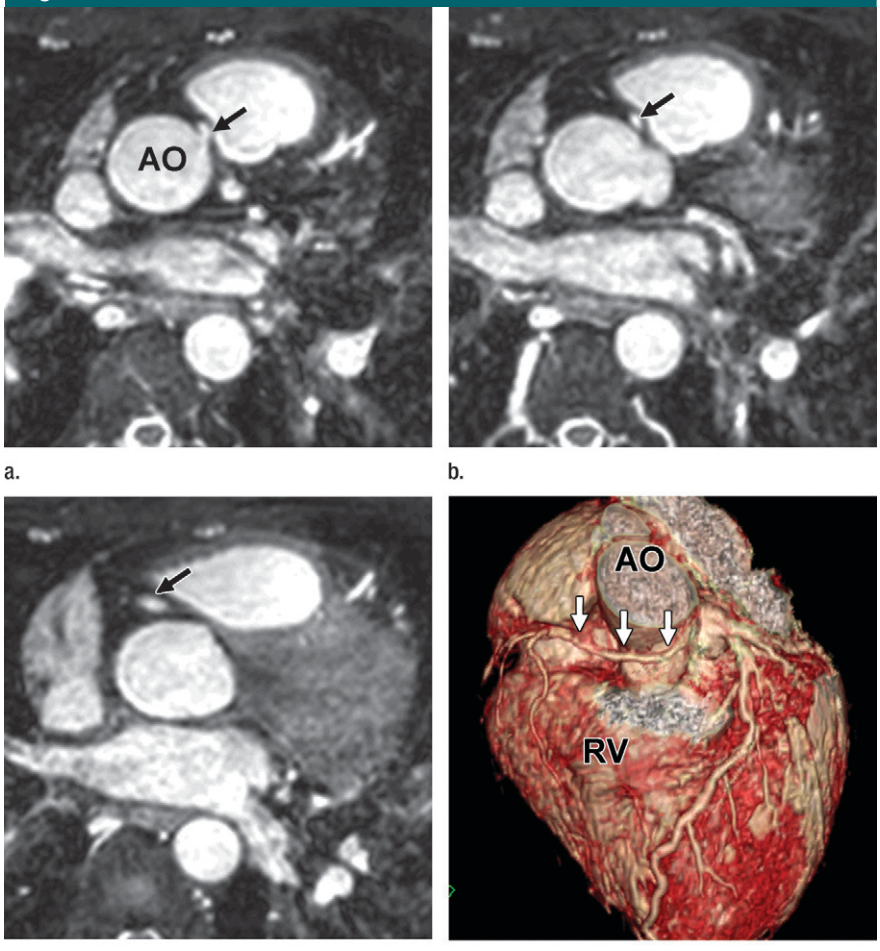



**Figure 4:** Nonenhanced 1.5-T whole-heart coronary MR angiography in a 34-year-old male patient with anomalous origin of the right coronary artery. MR angiography was performed because of history of ventricular tachycardia during exercise (4.6/2.3; flip angle, 90°; SENSE factor, two; field of view, 280 × 280 × 120 mm; acquisition matrices, 256 × 256 × 80; reconstruction matrices, 512 × 512 × 160). **(a–c)** Axial 3D source images and **(d)** volume-rendered image reveal anomalous origin of the right coronary artery from the left coronary sinus. Proximal portion of the right coronary artery (arrows) traverses between aorta *(AO)* and pulmonary artery. *RV* = right ventricle.

**Figure 5**

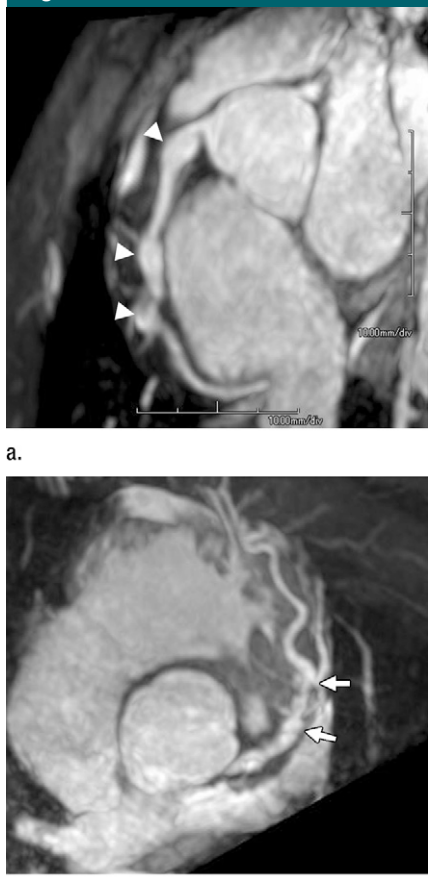



**Figure 5:** Nonenhanced 1.5-T whole-heart coronary MR angiography in a 19-year-old man with history of Kawasaki disease. Images were acquired by using an SSFP sequence with T2 preparation, spectral presaturation inversion-recovery fat saturation (4.6/2.3; flip angle, 90°; SENSE factor, four; field of view, 280 × 280 × 120 mm; acquisition matrices, 256 × 256 × 80; reconstruction matrices, 512 × 512 × 160). **(a)** Thin-section MIP image demonstrates aneurysms in the right coronary artery (arrowheads). **(b)** Thin-section MIP image shows aneurysm with small thrombus in the left anterior descending artery (arrows).

relatively young patients to radiation and should be considered as the first choice in patients who are suspected of having a coronary anomaly (Fig 4).

Kawasaki disease is an acute febrile illness in infants and produces coronary artery aneurysms in up to 25% of untreated cases (40). Coronary MR angiography provides noninvasive detection and size measurement of coronary artery aneurysms in patients with Kawasaki disease (41,42) (Fig 5). The size of a coronary artery aneurysm often changes over time and is associated with the risk of coronary thrombosis. For that reason, the serial assessment of aneurysmal size is important in stratifying risk in these patients and in treatment. To avoid radiation exposure from repeated coronary CT, coronary MR angiography should be used for the evaluation of coronary artery aneurysms in these patients.

There is a great interest in the noninvasive detection and characterization of coronary atherosclerotic plaque with MR, as myocardial infarction often results from rupture of a vulnerable plaque in the absence of a significant luminal stenosis in the coronary artery. However, the use of MR imaging to analyze coronary atherosclerotic plaque is challenging because of its small size and constant motion. T1-weighted two-dimensional and 3D black blood MR imaging sequences have been used to detect coronary atherosclerotic plaque (43) and to determine wall thickening of the coronary arteries (44). In a study (45), investigators

demonstrated increased wall thickness in the coronary artery by using MR imaging in a comparison of diabetic patients with nephropathy with diabetic patients without nephropathy. In carotid arteries, high-signal-intensity plaque on T1-weighted 3D MR images is shown to be associated with complicated plaques that may cause ischemic cerebrovascular events (46,47). In a recent study on the use of free-breathing T1-weighted 3D MR imaging, high-signal-intensity plaque in the coronary arteries was associated with positive remodeling, ultrasonographic (US) attenuation, lower CT Hounsfield units, and transient slow flow after percutaneous coronary intervention (48), indicating that free-breathing T1-weighted 3D MR imaging may be of value for noninvasive detection of complex coronary lesions (49). Late contrast-enhanced MR imaging with the use of extracellular gadolinium-based contrast agents is another method that has been proposed for coronary arterial wall imaging. Yeon et al (50) studied patients with stable CAD and found that late contrast enhancement in the coronary arterial wall was more often observed in calcified plaques than in noncalcified plaques or segments without plaque on CT images. In a more recent study by Ibrahim et al (51) on evaluation of patients with acute myocardial infarction, contrast enhancement in the segments with stenoses was significantly increased as compared with the contrast enhancement in the nonstenotic segments. Contrast-enhanced MR imaging 3 months after infarction revealed a significant reduction of contrast enhancement in stenotic segments. Late enhancement with nonspecific extracellular gadolinium-based contrast agents is likely to be associated with an increased distribution volume in the plaque by reason of inflammation, edema, or fibrosis. However, further studies are required to determine the relationship between contrast enhancement and histologic characteristics of the coronary artery plaque and to understand the value of this approach in patients who are suspected of having or are known to have CAD.

The capability to aid the performance of assessments of ventricular wall motion, myocardial ischemia, and viability is a major strength of cardiac MR imaging (6,7). The combination of coronary MR angiography with cine MR imaging, stress perfusion MR imaging, and late gadolinium-enhanced MR imaging provides a comprehensive assessment of patients with known CAD or patients who are suspected of having CAD. It should be noted that CT offers assessment of systolic ventricular function (52), detection of myocardial late enhancement (53), and delineation of stress-induced ischemia (54). At this point, however, these functional evaluations by using MR imaging have advantages over CT counterparts. Although left ventricular volume and ejection fraction can be assessed with retrospectively gated CT, left ventricular volumes determined by using CT are significantly higher than those measured with cine MR imaging and ejection fractions determined by using CT are significantly lower than those measured with cine MR imaging when β-blockers are administered prior to CT, because β-blockers significantly alter left ventricular function (55). Late contrast-enhanced CT allows imaging of infarcted myocardium with good correlation in the infarcted area when compared with late gadolinium-enhanced MR imaging. However, contrast-enhanced MR imaging has considerably higher contrast-to-noise ratios than does CT (56). The diagnostic performance of stress perfusion MR imaging is well established by researchers in many previous studies, including several multicenter studies and a meta-analysis (57,58). Contrast-enhanced CT with adenosine stress can be used to detect myocardial ischemia. In a recent study (59) on the use of dual-source CT, adenosine stress CT helped to identify stress-induced myocardial perfusion defects with a diagnostic accuracy comparable to that of single photon emission computed tomography, with a similar radiation dose. In addition, it also provided information on the presence and extent of coronary stenosis. Further studies with large numbers of patients are required to determine the benefit of performing coronary MR angiography in addition to stress perfusion MR imaging and late gadolinium-enhanced MR imaging (60).

## Diagnostic Accuracy

In a meta-analysis of 39 studies published from 1991 to 2004 (61), the sensitivity and specificity of coronary MR angiography for the detection of CAD were 75% and 85% in per-vessel analyses and 88% and 56% in per-patient analyses, respectively. In another meta-analysis in which 20 studies through 2009 were assessed (62), the mean sensitivity and specificity of coronary MR angiography were 87% and 70%, respectively. The sensitivity and specificity of coronary MR angiography varied considerably between the studies, owing to heterogeneity of pulse sequences and analytic methods that were used.

In a multicenter study (30) on the use of free-breathing 3D gradient-echo coronary MR angiography performed with the target-volume method, the sensitivity and specificity of coronary MR angiography for identifying patients with CAD were 93% and 42%, respectively. In the subgroup of patients with CAD of the left main coronary artery or three-vessel disease, coronary MR angiography demonstrated the sensitivity of 100% and the specificity of 85%, indicating the value of targeted-volume coronary MR angiography for excluding severe CAD. However, the introduction of SSFP sequences has considerably improved the diagnostic performance of coronary MR angiography. Jahnke et al (63) compared the diagnostic performance of breath-hold SSFP coronary MR angiography and free-breathing SSFP coronary MR angiography. Free-breathing coronary MR angiography was superior to breath-hold coronary MR angiography both in terms of image quality and diagnostic accuracy, with the sensitivity and specificity of 72% and 92%, respectively, by using free-breathing MR angiography and the sensitivity and specificity of 63% and 82%, respectively, by using breath-hold MR angiography. Kefer et al (64) reported the results of a head-to-head comparison between free-breathing coronary MR angiography and 16-section CT. MR and CT had similar sensitivity (75% vs 82%; the difference was not significant), specificity (77% vs 79%; the difference was not significant)

for the detection of significant stenoses on conventional coronary angiograms. It should be noted that coronary MR angiographic images in this study were acquired with a target-volume approach. Recent developments such as whole-heart coronary MR angiography, 32-channel cardiac coils, and high-field-strength MR imaging may improve the diagnostic accuracy of coronary MR angiography. Similarly, technical advances of CT have improved the diagnostic accuracy of coronary CT as well.

A whole-heart coronary MR angiographic approach enables delineation of more distal coronary segments than does the target-volume approach. In an initial feasibility study, acquisition of whole-heart coronary MR angiograms was successful in 34 (87%) of 39 patients, with the averaged acquisition duration of 13.8 minutes ± 3.8 (standard deviation) (13). In a single-center study (18) in 32 patients who were suspected of having CAD, whole-heart coronary MR angiography demonstrated a moderate sensitivity of 78% and a high specificity of 91% for the detection of significant CAD in a vessel-based analysis. Another single-center study (14) in which 131 subjects were assessed also demonstrated a moderate sensitivity of 78% and a high specificity of 96% for whole-heart coronary MR angiography. In a recent multicenter study (19) performed in 138 patients who were suspected of having CAD in the Japanese population, whole-heart coronary MR angiographic images were analyzed with a sliding thin-slab MIP method. Acquisition of whole-heart coronary MR angiograms was completed in 127 (92%) of 138 patients, with an average imaging time of 9.5 minutes ± 3.5. From MR angiographic images, the area under the receiver operating characteristic curve according to vessel-based analyses was 0.91 (95% confidence interval: 0.87, 0.95) and that according to patient-based analyses was 0.87 (95% confidence interval: 0.81, 0.93). The sensitivity, specificity, and positive and negative predictive values of whole-heart coronary MR angiography were 88%, 72%, 71%, and 88%, respectively, in a patient-based analysis. These values for detection of left main coronary artery disease or three-vessel disease were 89%, 100%, 100%, and 99%, respectively. When the effect of body mass index on diagnostic performance was analyzed, the area under the receiver operating characteristic curve was not significantly different between the patients with a body mass index of less than 25 kg/m$^2$ and those with a body mass index of 25 kg/m$^2$ or greater at any level of analysis (patient, vessel, and segment).

Higher magnetic field strength may improve the detection of CAD with coronary MR angiography (Fig 6). Because of increased radiofrequency field inhomogeneity and energy deposition at high field strength, the gradient-echo sequence instead of the SSFP sequence has better clinical performance at 3.0 T (32,33). In a recent study by Yang et al (4), the diagnostic performance of 3.0-T contrast-enhanced whole-heart coronary MR angiography was evaluated in 69 patients who were suspected of having CAD. MR angiographic data were acquired during a slow infusion of double-dose extracellular gadolinium-based contrast medium by using a short inversion time inversion-recovery preparation. The sensitivity and specificity of 3.0-T whole-heart coronary MR angiography were 94% and 82% in a patient-based analysis, suggesting that the diagnostic performance of 3.0-T contrast-enhanced coronary MR angiographic approaches that of 64-section CT.

**Figure 6**

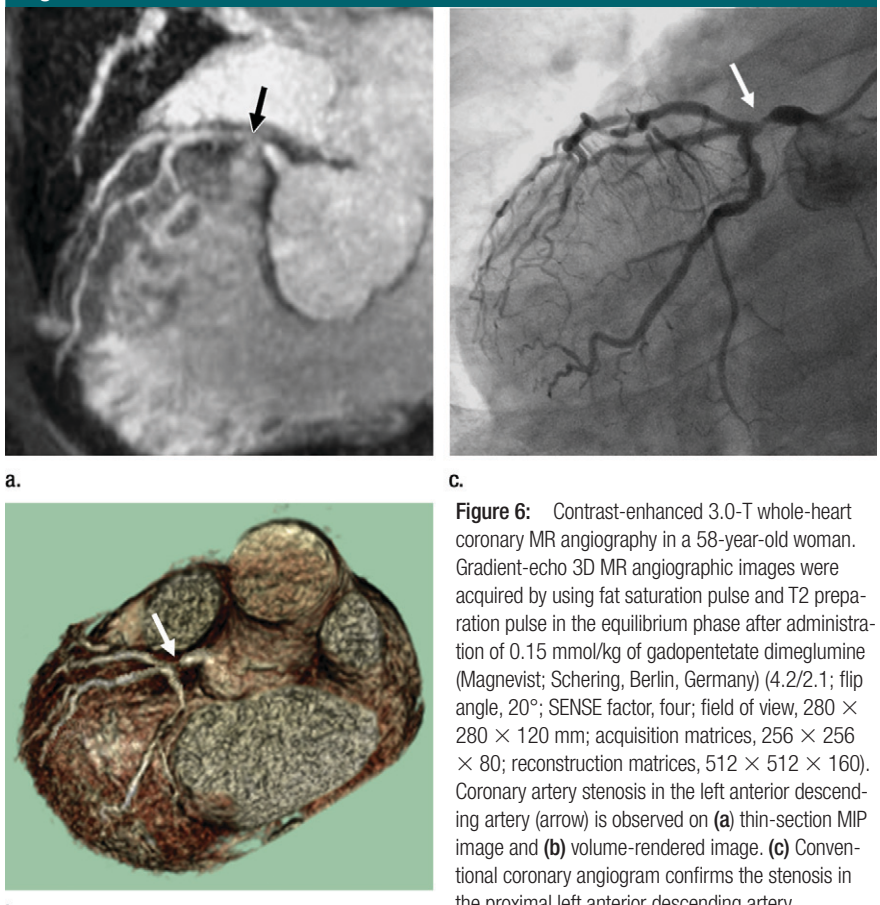



**Figure 6:** Contrast-enhanced 3.0-T whole-heart coronary MR angiography in a 58-year-old woman. Gradient-echo 3D MR angiographic images were acquired by using fat saturation pulse and T2 preparation pulse in the equilibrium phase after administration of 0.15 mmol/kg of gadopentetate dimeglumine (Magnevist; Schering, Berlin, Germany) (4.2/2.1; flip angle, 20°; SENSE factor, four; field of view, 280 × 280 × 120 mm; acquisition matrices, 256 × 256 × 80; reconstruction matrices, 512 × 512 × 160). Coronary artery stenosis in the left anterior descending artery (arrow) is observed on **(a)** thin-section MIP image and **(b)** volume-rendered image. **(c)** Conventional coronary angiogram confirms the stenosis in the proximal left anterior descending artery.

## Training Issues

MR of the coronary arteries is a complex examination to perform, and interpretation is also complex. Results depend on operator experience, even after introduction of whole-heart coronary MR

**Figure 7**

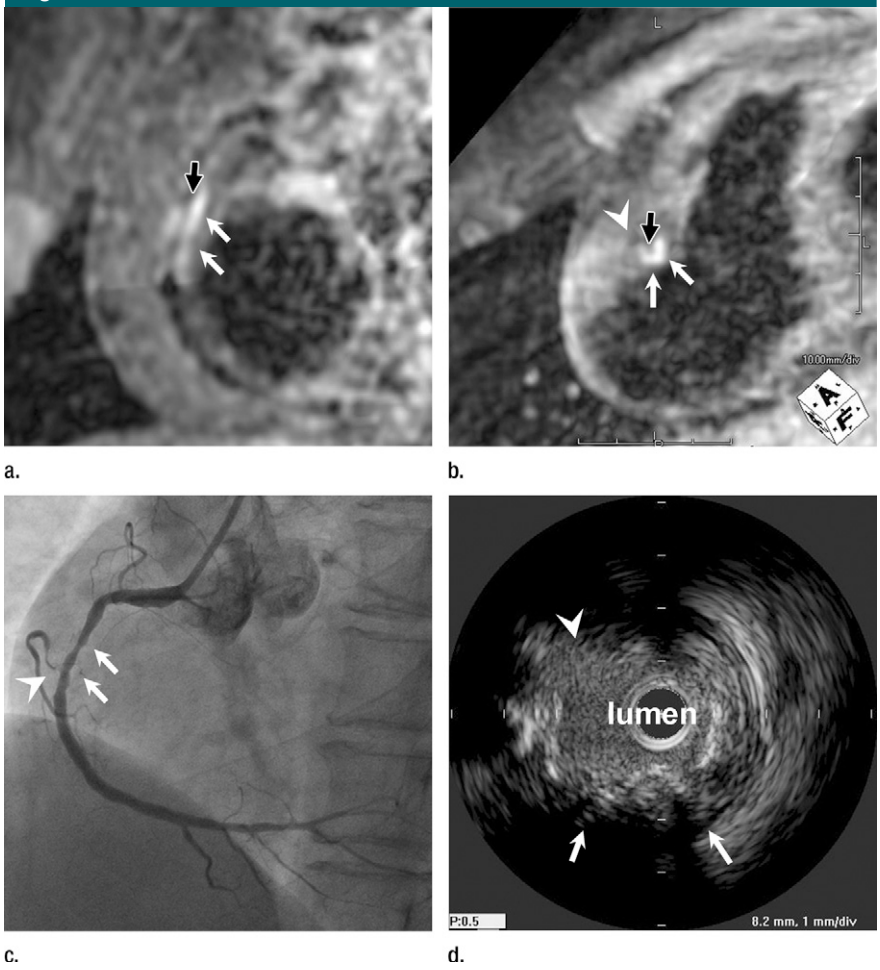



**Figure 7:** Black blood T1-weighted 3D whole-heart coronary images acquired with 3.0-T MR imager and 32-channel cardiac coils in a 71-year-old man with chest pain. T1-weighted 3D turbo spin-echo pulse sequence was used with 1 R-R interval/39 msec; flip angle, 90°; SENSE factor, four; field of view, 320 × 256 × 140 mm; acquisition matrices, 192 × 154 × 80; reconstruction matrices, 512 × 512 × 160). **(a)** Multiplanar reconstructed image of the right coronary artery exhibits high signal intensity along the coronary vessel wall in the middle portion of the right coronary artery (white arrows). Black arrow (also for **b**) indicates lumen of the right coronary artery. **(b)** Cross-sectional MPR image of the right coronary artery shows high-signal-intensity plaque (white arrows) in the right coronary artery located on the opposite side of the right ventricular branch (arrowhead). **(c)** Conventional coronary angiogram shows moderate coronary artery stenosis. **(d)** Cross-sectional intravascular US image shows eccentric soft plaque in the middle portion of the right coronary artery (arrows). Arrowheads on **b**, **c**, and **d** indicate position of right ventricular branch of the right coronary artery. (Reprinted, with permission, from reference 69.)

angiography. In addition, the available pulse sequences for coronary MR angiography vary considerably from one MR vendor to another. The data acquisition window and electrocardiographic trigger delay time in the cardiac cycle need to be carefully adjusted by monitoring the motion of the coronary artery at cine MR imaging. Thus, the quality of the results depends on operator skill. Because of these factors, coronary MR angiography is not currently routinely performed in many institutions. Standardization of coronary MR angiographic protocols and training for technologists are important for the widespread clinical use of coronary MR angiography. In the future, it is hoped that the process to determine the patient-specific acquisition window in the cardiac cycle will be further automated (65).

As for the difficulty in interpretation, there is no substantial difference between coronary MR angiography and CT if the reader has sufficient experience in reading images obtained with both modalities. However, the number of hospitals performing coronary CT is much larger than is the number of those performing coronary MR angiography. Insufficient numbers of cardiac imaging practitioners with expertise in coronary MR angiography is one of the current major limitations of MR assessments of the coronary arteries.

## Summary

Coronary MR angiography allows for noninvasive visualization of the coronary artery without exposing the patients to ionizing radiation. However, long image time, lower spatial resolution, and operator dependency are major limitations of coronary MR angiography. Technical advances, including high-field-strength MR imaging and multichannel cardiac coils, may provide more accurate detection of CAD with reduced imaging time. While cardiac CT research studies have grown exponentially in recent years (66), the number of studies on coronary MR angiography is still limited. An increase in trained investigators and multicenter studies employing up-to-date MR angiographic techniques are essential to prove the value of coronary MR angiography for ruling out significant CAD. MR imaging has a great potential in its capability to aid assessment of the burden of atherosclerotic disease in the vessel wall (67,68). Detection of high-signal-intensity plaque by using nonenhanced T1-weighted MR imaging and late gadolinium-enhanced MR imaging of the coronary arterial wall are promising approaches for characterizing coronary plaque. Further work is required to develop and optimize imaging sequences for coronary plaque MR imaging at 3.0 T (Fig 7).

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