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Published online before print
 10.1148/radiol.2371040830
 Radiology 2005; 237:316–321

Abbreviations:

LAD = left anterior descending
 LCX = left circumflex
 RCA = right coronary artery
 3D = three-dimensional

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See Materials and Methods for pertinent disclosures.

Author contributions:

Guarantor of integrity of entire study, H.S.; study concepts/study design or data acquisition or data analysis/interpretation, all authors; manuscript drafting or manuscript revision for important intellectual content, all authors; approval of final version of submitted manuscript, all authors; literature research, H.S.; clinical studies, H.S., Y.I., N.S., T.H., M.M.; statistical analysis, H.S., Y.I.; and manuscript editing, H.S.

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Assessment of Coronary Arteries with Total Study Time of Less than 30 Minutes by Using Whole-Heart Coronary MR Angiography

This study had institutional review board approval, and all patients gave informed consent. The purpose of this study was to prospectively evaluate the use of whole-heart three-dimensional (3D) coronary magnetic resonance (MR) angiography in patients suspected of having coronary artery disease. Whole-heart coronary MR angiography was performed in 39 patients (30 men and nine women; mean age, 63.9 years \pm 15.6 [standard deviation]) by using a steady-state free precession sequence with free breathing. Twenty patients (16 men and four women; mean age, 64.9 years \pm 11.7) also underwent conventional coronary angiography. MR angiography was successfully completed in 34 of 39 patients (87%); the average imaging time was 13.8 minutes \pm 3.8. Sensitivity and specificity of MR angiography for detecting significant stenosis were 82% (14 of 17 arteries) and 91% (39 of 43 arteries), respectively. Whole-heart coronary MR angiography with a navigator-gated steady-state sequence can enable reliable 3D visualization of the coronary arteries in patients suspected of having coronary artery disease.

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Coronary artery disease is one of the leading causes of morbidity and mortality in industrialized countries (1). Considerable progress has been made in the field of noninvasive imaging of the coronary arteries with magnetic resonance (MR) angiography and electron-beam computed tomography (CT) during the past decade (2–10). Recently, contrast material-enhanced multi-detector row spi-

ral CT has emerged as a noninvasive method that can permit visualization of the coronary artery lumen and detection of stenoses (11,12). From a patient's viewpoint, coronary MR angiography is probably preferable to the CT method for detecting coronary artery disease because it does not expose the patient to radiation or require a rapid injection of iodinated contrast material. Results of a previous multicenter study (13) demonstrated that three-dimensional (3D) coronary MR angiography enables the accurate detection of coronary artery disease in the left main coronary artery and in the proximal segments of the left anterior descending (LAD) artery, left circumflex (LCX) artery, and right coronary artery (RCA). Coronary MR angiography, however, remains time consuming because only a limited portion of the coronary artery tree is imaged for each targeted double-oblique 3D volume acquisition, necessitating the acquisition of repeated 3D images to cover all the coronary arteries.

Whole-heart coronary MR angiography with a navigator-gated 3D steady-state free precession sequence has recently been introduced by Weber et al (14) as a method that can enable visualization of all three major coronary arteries within a single 3D acquisition. This approach allows subsequent reformatting for visualizing the coronary arteries. It is not clear, however, whether this approach can be used in most patients. Thus, the purpose of this study was to prospectively evaluate whole-heart 3D coronary MR angiography in patients suspected of having coronary artery disease.

Materials and Methods

N.K. and M.V.C. are employees of Philips Medical Systems. The authors who are not employees of Philips Medical Systems (H.S., Y.I., N.S., T.H., K.M., K.T.) had control of inclusion of any data and in-

formation that might present a conflict of interest for those authors who are employees of that industry.

Patients

This study protocol was approved by the institutional review board of Mie University Hospital, and all patients gave informed consent. Thirty-nine patients (30 men and nine women; mean age, 63.9 years \pm 15.6 [standard deviation]) were evaluated in this study. If the patients met our inclusion criteria, they were consecutively recruited from among outpatients suspected of having coronary artery disease from September 2003 through December 2003. Patients with contraindications to MR imaging (eg, presence of a pacemaker, claustrophobia, irregular heart rate) and those with unstable hemodynamic parameters were excluded. Conventional coronary angiography was not required as an inclusion criterion of this study.

Imaging

MR images were obtained with a 1.5-T unit (Intera Nova-Dual; Philips Medical Systems, Best, the Netherlands). Five-element cardiac synergy receiver coils were used for radiofrequency reception. The coils had two front elements and three back elements. A four-lead vector electrocardiogram was obtained for cardiac gating. Initial survey images were obtained in three orthogonal directions to help determine the position of the heart and diaphragm. Then, a reference image was obtained so that we could evaluate the individual coil sensitivities for subsequent sensitivity-encoding imaging (15).

To determine the motion of the RCA, multiphase cine MR images were obtained in the transverse plane with a steady-state free precession pulse sequence and the following parameters: repetition time msec/echo time msec, 2.6/1.3; flip angle, 60°; acquisition matrix, 160 \times 160; reconstruction matrix, 256 \times 256; number of cardiac phases, 50; temporal resolution, 15–20 msec; and sensitivity-encoding factor, 3.0. Scout images, reference images, and cine MR images were obtained during free breathing (Fig 1). The motion of the RCA was visually assessed by scrolling through the transverse cine MR images obtained during the cardiac phases. A subject-specific trigger delay time and an interval of minimal RCA motion during mid-diastole were determined for the whole-heart coronary MR angiography acquisition (16).

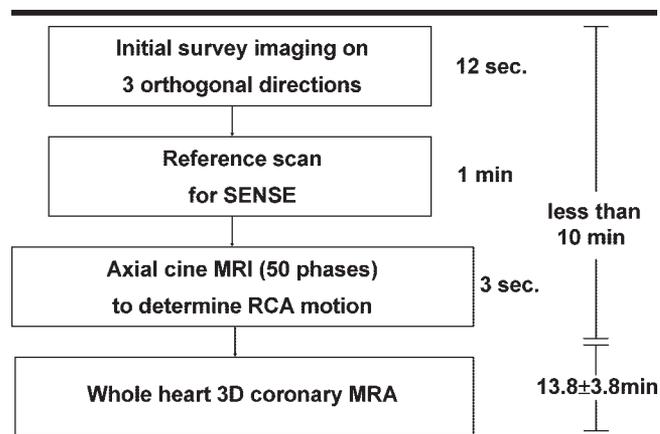


Figure 1. Diagram shows study protocol used for whole-heart coronary MR angiography (MRA). The entire MR study could be completed within 30 minutes and during free breathing. SENSE = sensitivity encoding.

After the position of the heart was determined with initial coronal survey images, 3D coronary MR images covering the entire heart were obtained in a transaxial orientation by using a magnetization-prepared 3D centric-ordered segmented steady-state free precession sequence (4.6/2.3; flip angle, 90°; number of signals acquired per cardiac cycle, 20–50; sensitivity-encoding factor, 2.0; bandwidth per pixel, 678.5 Hz; field of view, 280 \times 280 \times 120 mm; acquisition matrix, 256 \times 256 \times 80; reconstruction matrix, 512 \times 512 \times 160; and reconstructed voxel size, 0.55 \times 0.55 \times 0.75 mm). Magnetization preparation was achieved by applying a T2-weighted preparation pulse with an echo time of 50 msec and a frequency-selective fat-saturation pulse followed by a spoiler gradient. An automated shim procedure was applied to the volume of the entire heart. For real-time respiratory gating and real-time correction of the 3D volume in the craniocaudal direction, a navigator echo was acquired from a cylindrical region that was generated by a two-dimensional excitation pulse perpendicular to the right hemidiaphragm with a gating window of 5 mm. A gadolinium chelate was not administered for coronary MR angiography. For each patient, a technologist recorded the acquisition time for 3D coronary MR images, the heart rate, the length of the data acquisition window in the cardiac cycle (in milliseconds), and the mean time between the electrocardiographic R wave trigger and the start of image acquisition.

Image Interpretation

All MR images were transferred to a workstation (Precision 450; Dell, Round

Rock, Tex) with image reconstruction software. Curved multiplanar reformation was performed by using research software (SoapBubble Tool V2.1; Philips Medical Systems) that was written in Interactive Data Language (Research Systems, Boulder, Colo). A curved subvolume encompassing the coronary arterial segments was interactively selected in a 3D whole-heart coronary MR angiographic data set, and multiple coronary segments were simultaneously displayed in one two-dimensional representation (17). Three-dimensional volume-rendered images were generated with commercially available image analysis software (Virtual Place Advance; Aze, Tokyo, Japan).

Visible vessel length was assessed for the RCA and the LAD and LCX arteries. Coronary MR angiographic images reconstructed with curved multiplanar reformation and volume-rendering techniques were scored in consensus by two radiologists (H.S., Y.I.) with 15 and 5 years of experience with MR imaging of the heart, respectively. The visibility of each coronary artery segment was rated on a four-point scale in which a score of 1 indicated poor visibility (coronary vessel was barely seen or image was noisy); a score of 2, marginal visibility (coronary vessel was visible but confidence for diagnosis was low); a score of 3, good visibility (coronary artery was adequately visualized and image was of diagnostic quality); and a score of 4, excellent visibility (coronary artery was well depicted). For image quality assessment, the RCA and the LAD artery were divided into proximal, middle, and distal segments, and the LCX artery was divided into proximal and distal segments.

TABLE 1
Mean Qualitative Scores for Each Coronary Artery Segment

| Artery | Mean Score | | No. of Patients with a Score of at Least 3 (n = 34)* |
|-----------|-------------------------------------|-----------------------|--|
| | With Curved Multiplanar Reformation | With Volume Rendering | |
| RCA | | | |
| Proximal | 3.9 ± 0.4 | 3.9 ± 0.4 | 33 (97) |
| Middle | 3.8 ± 0.5 | 3.8 ± 0.7 | 33 (97) |
| Distal | 3.6 ± 0.6 | 3.7 ± 0.6 | 33 (97) |
| Left main | 3.7 ± 0.5 | 3.7 ± 0.6 | 33 (97) |
| LAD | | | |
| Proximal | 3.7 ± 0.5 | 3.6 ± 0.7 | 33 (97) |
| Middle | 3.7 ± 0.5 | 3.7 ± 0.5 | 33 (97) |
| Distal | 3.4 ± 0.7 | 3.3 ± 0.9 | 32 (94) |
| LCX | | | |
| Proximal | 3.7 ± 0.5 | 3.5 ± 0.7 | 33 (97) |
| Distal | 3.2 ± 0.9 | 3.4 ± 0.7 | 32 (94) |

* Numbers in parentheses are percentages.

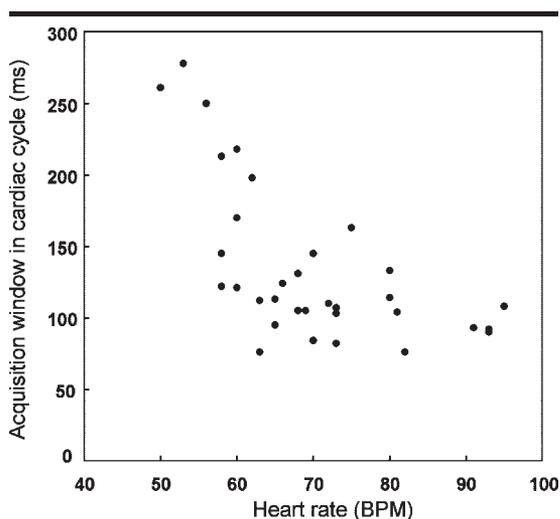


Figure 2. Graph shows relationship between heart rate and the subject-specific data acquisition windows in the cardiac cycle. An inverse relationship is seen between the heart rate and the data acquisition window in the cardiac cycle. The mean heart rate and data acquisition window in 34 patients were 69.7 beats per minute (BPM) ± 11.7 (range, 58–93 beats per minute) and 133.4 msec ± 54.4 (range, 76–278 msec), respectively.

The presence of significant coronary artery lesions at whole-heart 3D coronary MR angiography was evaluated in consensus by two radiologists (H.S., Y.I.) who did not have knowledge of the results at conventional coronary angiography. Lesions with a diameter reduction of at least 50% at coronary MR angiography were visually determined and recorded in the major coronary arterial territories, including the RCA, the left main anterior descending artery, the LAD artery, and the LCX artery.

Conventional Coronary Angiography

Comparison between whole-heart 3D coronary MR angiography and conventional coronary angiography was performed in 20 patients (16 men and four women; mean age, 64.9 years ± 11.7). These patients were among the 39 who had previously successfully undergone whole-heart coronary MR angiography, and selective coronary angiography was performed within 2 weeks of the MR imaging study. Conventional coronary an-

giography was performed for diagnostic purposes in these patients. Conventional coronary angiograms were evaluated by an independent observer (K.M.) with 18 years of experience in coronary angiography. The observer was blinded to the results of coronary MR angiography. Lesions with a diameter reduction of at least 50% at quantitative coronary angiography were considered to be significant. The presence or absence of significant stenoses in the coronary arteries was recorded in the major coronary artery territories, including the RCA, the left main descending artery, the LAD artery, and the LCX artery.

Statistical Analysis

All values are expressed as means ± standard deviations. The statistical significance of differences between the lengths of coronary arteries was evaluated with a paired bidirectional Student *t* test. All measurements were noted on an electric data sheet (Excel 2003; Microsoft, Redmond, Wash) and subjected to statistical analysis with statistical software (SPSS; SPSS, Chicago, Ill). *P* values of less than .05 were considered to indicate a statistically significant difference. The presences and absences of significant stenoses that were independently and blindly determined for three major coronary arteries on coronary MR angiograms and conventional coronary angiograms were noted on an electric data sheet. The diagnostic results for the detection of significant stenoses in the major coronary arteries were expressed as sensitivity, specificity, accuracy, and positive and negative predictive values. The diagnostic results for the detection of patients who had at least one coronary artery with significant stenosis were also expressed as sensitivity, specificity, accuracy, and positive and negative predictive values.

I Results

Image Acquisition

Whole-heart coronary MR angiography was completed in 34 of the 39 patients (87%) with an average imaging time of 13.8 minutes ± 3.8 (range, 6.8–23.8 minutes). In the remaining five patients (13%), image acquisition was interrupted by an operator because drift of the position of the diaphragm over time during MR image acquisition resulted in a low navigation efficiency in these patients; hence, the total MR study time in these patients exceeded 30 minutes. Fig-

ure 2 illustrates the relationship between heart rate and the data acquisition windows in which the motion of the RCA on cine MR images was minimal. The mean heart rate and data acquisition window were 69.7 beats per minute \pm 11.7 (range, 58–93 beats per minute) and 133.4 msec \pm 54.4 (range, 76–278 msec), respectively. The mean time between electrocardiographic R wave triggering and the start of image acquisition was 515.6 msec \pm 195.6.

Image Quality

Whole-heart coronary MR angiograms obtained in a patient with normal coronary arteries and in a patient with significant coronary artery disease are shown in Figures 3 and 4, respectively. High-quality images (images with a score of at least 3) were obtained in all segments of the major coronary arteries in 32 of the 34 patients (94%) (Table 1). Table 2 provides a summary of the lengths of the major coronary arteries visualized at whole-heart coronary MR angiography. The visualized length of the LAD artery was significantly longer with the volume-rendering method than with curved multiplanar reformation ($P < .05$).

Detection of Stenoses in Coronary Arteries

Of the 20 patients who underwent selective coronary angiography, 12 were found to have significant coronary artery disease (eight patients had single-vessel disease, three had double-vessel disease, and one had triple-vessel disease). The sensitivity, specificity, accuracy, and positive and negative predictive values of whole-heart 3D coronary MR angiography in the detection of significant stenoses in the major coronary arteries were 82% (14 of 17 arteries), 91% (39 of 43 arteries), 88% (53 of 60 arteries), 78% (14 of 18 arteries), and 93% (39 of 42 arteries), respectively (Table 3). The corresponding values for the detection of patients with at least one coronary artery stenosis were 83% (10 of 12 patients), 75% (six of eight patients), 80% (16 of 20 patients), 83% (10 of 12 patients), and 75% (six of eight patients), respectively.

Discussion

In the current study, we obtained whole-heart 3D coronary MR angiograms with a total examination time of less than 30 minutes. All major coronary arteries, including distal segments, were

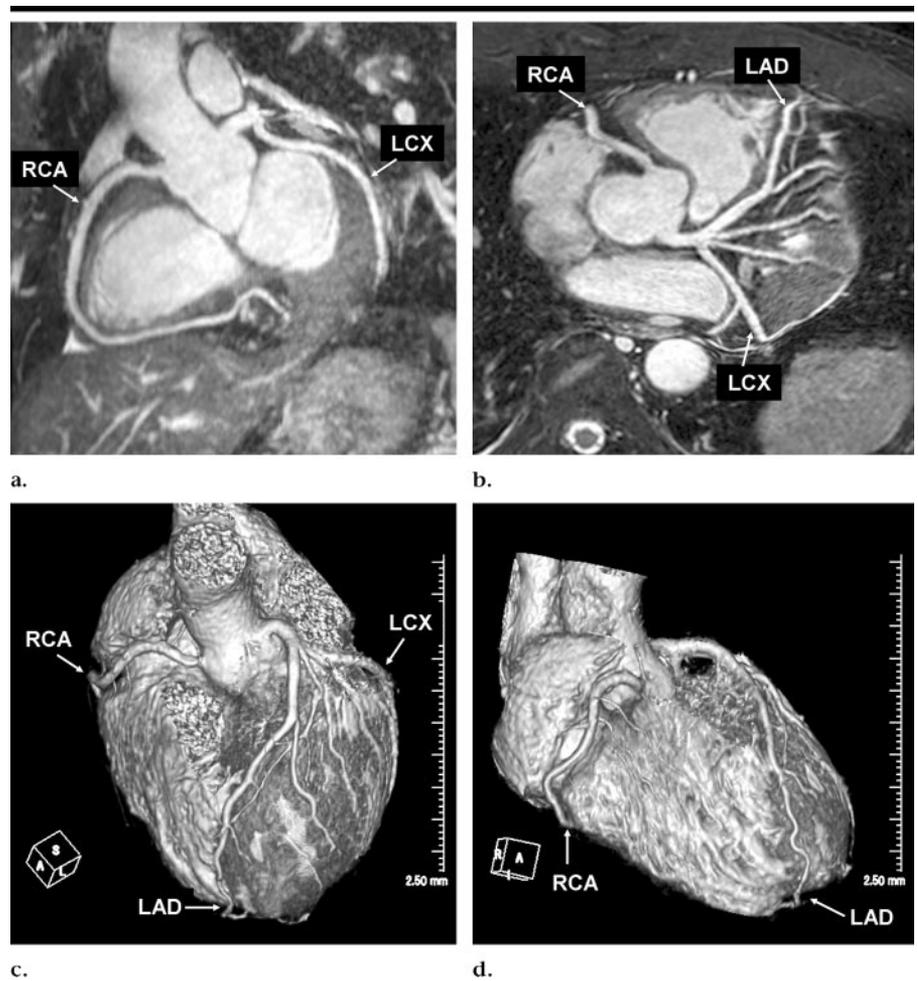


Figure 3. Reformatted whole-heart coronary MR angiograms (4.6/2.3, navigator-gated 3D steady-state free precession sequence with fat saturation and T2-weighted preparation) in 42-year-old man with normal coronary arteries. (a) Left anterior oblique image reformatted with curved multiplanar reformation clearly depicts RCA and LCX artery. (b) Oblique transverse image reformatted with curved multiplanar reformation shows left main coronary artery, LAD artery, and proximal portions of the RCA and the LCX artery. (c) Left anterior oblique volume-rendered image is useful for general anatomic recognition of the LAD and LCX arteries. (d) Right anterior oblique volume-rendered image clearly delineates the RCA and its right ventricular branches.

clearly visualized by using our current approach in 94% (32 of 34) of the patients in whom data acquisition was completed and in 82% (32 of 39) of the patients enrolled in this study. In addition, whole-heart 3D coronary MR angiography depicted 14 of the 17 significant coronary artery stenoses (82%) identified at conventional coronary angiography, which indicates the value of this approach in the assessment of patients suspected of having coronary artery disease.

Results of a previous multicenter study by Kim et al (13) demonstrated that coronary MR angiography had high sensitivity, high negative predictive value, and high overall accuracy in the detection of coronary artery disease in the left main

coronary artery, as well as in the proximal and middle segments of the RCA and the LAD artery; these findings are indicative of the value of coronary MR angiography in identifying or excluding left main coronary artery and three-vessel disease. Because Kim et al used targeted volume 3D acquisitions in 3-cm-thick slabs, coverage of the coronary artery trees in the distal segments was relatively limited and the percentages of segments for which images could be assessed ranged from 68% (for the middle part of the LCX artery) to 93% (for the proximal and middle parts of the RCA). Watanabe et al (5) more recently evaluated the coverage of coronary artery segments with targeted 3D coronary MR angiography. Of 70 segments, including distal portions

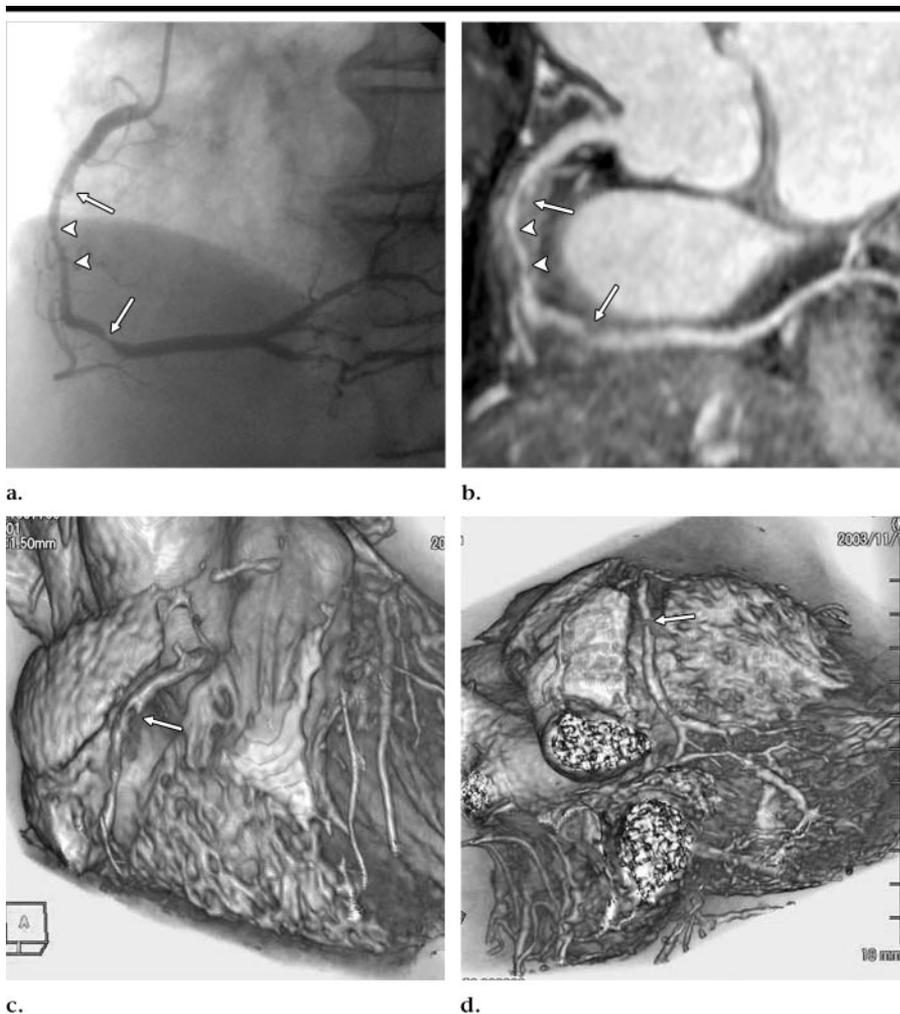


Figure 4. Coronary artery images obtained in 78-year-old man with significant stenoses in the RCA. (a) Conventional coronary angiogram in left anterior oblique view shows significant luminal stenoses (arrows) in the proximal and middle parts of the RCA and diffuse atherosclerotic changes (arrowheads). (b) Left anterior oblique whole-heart coronary MR angiogram (4.6/2.3, navigator-gated 3D steady-state free precession sequence with fat saturation and T2-weighted preparation) reformatted with curved multiplanar reformation shows significant luminal narrowing (arrows) in the proximal and middle parts of the RCA and diffuse atherosclerotic plaque (arrowheads). (c) Oblique coronal volume-rendered image from whole-heart coronary MR angiography reveals a significant stenosis (arrow) in the proximal RCA. (d) Oblique transverse volume-rendered image from whole-heart coronary MR angiography demonstrates luminal narrowing (arrow) in the more distal part of the RCA.

TABLE 2
Length of Major Coronary Arteries Visualized at Whole-Heart Coronary MR Angiography

| Artery | Length Visualized with Curved Multiplanar Reformation (cm) | Length Visualized with Volume Rendering (cm) | P Value |
|--------|--|--|---------|
| RCA | 11.8 ± 2.5 | 12.8 ± 3.4 | .151 |
| LAD | 9.8 ± 2.2 | 11.3 ± 3.7 | .012 |
| LCX | 6.9 ± 2.5 | 7.3 ± 3.4 | .412 |

of the coronary arteries, 49 (70%) were fully demonstrated on diagnostic-quality images. With the whole-heart approach,

long segments of all major coronary arteries can be imaged. The percentage of distal segments that exhibited good or

excellent image quality was greater than 90% for all major coronary arteries in the present study.

The average acquisition time with whole-heart coronary MR angiography was 13.8 minutes ± 3.8 in our study, which is longer than that required for each 3D acquisition in the targeted volume approach by a factor of two to three. However, because repeated 3D volume acquisitions are required in the targeted volume approach to cover the entire coronary artery tree (5), the total acquisition time involved in the whole-heart approach is at least comparable to or less than that involved in the targeted volume approach. Furthermore, whole-heart coronary MR angiography can be performed without knowledge of the position and course of the coronary artery. We obtained only an initial survey image (12 seconds), a reference image for sensitivity-encoding imaging (1 minute), and a cine MR image in one transaxial plane to determine RCA motion (3 seconds) before starting the whole-heart coronary MR acquisition. A considerable time savings was achieved by eliminating the time-consuming three-point planning used in the targeted volume approach. In our study, the total MR examination time was less than 30 minutes, which is substantially shorter than that previously reported (approximately 70 minutes) with the targeted volume approach (13). It should also be noted that planning the 3D volume for whole-heart coronary MR angiography is quite simple, and the risk of planning error seems to be substantially reduced compared with the risk with the targeted volume method.

We used subject-specific acquisition windows for whole-heart coronary MR imaging (16). We assessed the motion of the RCA by acquiring high-temporal-resolution cine MR images because the motion of the RCA was more extensive than that of the left coronary arteries by a factor of at least two (18). In contrast to previous investigators (14,16), we obtained cine MR images in the transaxial imaging plane instead of the double-oblique imaging plane perpendicular to the vessel to minimize the total examination time. The diastolic quiescent period was well determined in all subjects with this approach. In patients with lower heart rates, the prolonged diastolic quiescent period enabled the use of longer acquisition windows, which substantially reduced the imaging time in such patients. The quiescent period was less than 100 msec in five patients in our study. However, as we found and as Weber et al (14)

previously observed, excellent coronary MR angiographic images can be obtained in patients with higher heart rates and shorter diastolic quiescent periods.

Contrast-enhanced multi-detector row spiral CT has recently been introduced as a method for noninvasive visualization of the coronary arteries (10,11). In the present study, the sensitivity (82%) and specificity (91%) of whole-heart coronary MR angiography in the detection of significant coronary artery disease were not as good as those reported for multi-detector row CT (sensitivity, 92%; specificity, 93%) by Ropers et al (12). Compared with multi-detector row CT, however, the whole-heart coronary MR angiography approach has the advantage of requiring neither exposure to ionizing radiation nor injection of contrast material.

Several limitations in this study should be acknowledged. Whole-heart coronary MR angiography was not completed in five of the 39 patients (13%) owing to drift of the diaphragm position over time during image acquisition. The use of motion-adapted gating may increase the imaging efficiency in patients who show irregularities in their breathing patterns (19). Imaging time with whole-heart coronary MR angiography is substantially longer than that with contrast-enhanced multi-detector row spiral CT, and image data were obtained during free breathing in the present study. The acquisition of data during free breathing leads to volume averaging and motion blurring at coronary MR angiography. We did not evaluate the degree of stenosis at coronary MR angiography. As demonstrated in Figure 4, stenosis of the coronary arteries seemed to be overestimated with coronary MR angiography in comparison with stenosis estimated with conventional coronary angiography. Overestimation of stenosis at MR angiography has previously been reported to occur in the abdomen, pelvis, and extremities (20). Partial volume averaging due to the insufficient spatial resolution of MR angiography and high-velocity turbulent flow at the point of luminal narrowing may help explain the overestimation of stenoses. The patient population was small in the present study, and sensitivity and specificity were calculated in this small number of patients. Further multicenter studies are required to help determine the diagnostic value of this technique in the detection and exclusion of significant coronary artery disease.

TABLE 3
Detection of Significant Stenoses in Coronary Arteries in 20 Patients

| Parameter | Per Major Coronary Artery* | Per Patient |
|-------------------------------|----------------------------|-------------|
| Sensitivity (%) | 82 (14/17) | 83 (10/12) |
| Specificity (%) | 91 (39/43) | 75 (6/8) |
| Accuracy (%) | 88 (53/60) | 80 (16/20) |
| Positive predictive value (%) | 78 (14/18) | 83 (10/12) |
| Negative predictive value (%) | 93 (39/42) | 75 (6/8) |

Note.—Numbers in parentheses are numbers of arteries or patients.

* Arteries include the RCA and the left main, LAD, and LCX arteries.

In conclusion, whole-heart coronary MR angiography with a navigator-gated steady-state sequence can enable reliable 3D visualization of the entire coronary artery tree with a total study time of less than 30 minutes in patients suspected of having coronary artery disease.

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