3.0T Whole-Heart Coronary Magnetic Resonance Angiography Performed With 32-Channel Cardiac Coils
A Single-Center Experience

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Background—Whole-heart coronary magnetic resonance angiography (MRA) is a promising method for noninvasive, radiation-free detection and exclusion of obstructive coronary artery disease; however, the required imaging time and robustness of the technique are not yet satisfactory. We evaluated the value of whole-heart coronary MRA at 3.0T using a 32-channel cardiac coil, which reduces image-acquisition times and hence allows to increase the clinical throughput.

Methods and Results—A total of 110 consecutive patients with suspected coronary artery disease referred for clinically indicated conventional coronary angiography were included in this prospective study. Acquisition of 3.0T coronary MRA data was done by using 32-channel receiver coils. An ECG-triggered, navigator-gated, inversion-recovery prepared, segmented gradient-echo sequence was used for image acquisition with an acceleration factor of 3 in the phase-encoding direction using generalized auto-calibrating partially parallel acquisitions reconstruction. Acquisition of coronary MRA was successfully completed in 101 of 110 (92%) patients with average imaging time of 7.0±1.8 minutes. The sensitivity, specificity, positive and negative predictive value of coronary MRA on a patient-based analysis were 95.9% (47/49, 95% CI, 86.0%–99.4%), 86.5% (45/52, 95% CI, 74.2%–94.4%), 87.0% (47/54, 95% CI, 75.1%–94.6%) and 95.7% (45/47, 95% CI, 85.4%–99.4%), respectively.

Conclusions—Whole-heart coronary MRA at 3.0T using a 32-channel cardiac coil allows high overall accuracy for detecting significant coronary artery disease with reduced imaging time. It has potential to be a robust and alternative technique for ruling out significant coronary artery disease.


Key Words: magnetic resonance angiography ▼ coronary arteries ▼ 3.0T

The current gold standard for the assessment of coronary artery disease (CAD) remains invasive x-ray coronary angiography, which exposes patients to ionizing radiation and involves certain risk of complications. Since the implementation of multislice computed tomography (CT), noninvasive coronary imaging using 64-slice CT has proven to be highly accurate as a diagnostic tool for the detection of coronary artery stenoses in the clinical routine.1,2 However, radiation exposure to patients and its possible risk of cancer induction have remained issues of great concern.3 Over the past 15 years, the continuous improvement in magnetic resonance (MR) imaging technology allows noninvasive, radiation-free, comprehensive evaluation of CAD.4,6 Initial experiences have shown that the diagnostic accuracy of contrast-enhanced whole-heart coronary MR angiography (MRA) at 3.0T in detecting coronary artery stenosis approaches that of 64-slice CT.7 Nevertheless, coronary MRA procedure remains lengthy and has limited the general applicability of this test.8,9 Further reductions in coronary MRA acquisition time have been made possible recently with the novel multichannel cardiac coils and high parallel imaging factors.10 The use of parallel imaging at higher magnetic fields has been shown to be extremely promising for minimizing the many challenges for high-resolution, high-speed coronary MRA.

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We have therefore conducted a prospective study to evaluate the diagnostic performance of 3.0T whole-heart coronary MRA using a 32-channel cardiac coil compared with quantitative x-ray coronary angiography in patients with suspected CAD.

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Methods

Study Population
From January 2009 to July 2010, a total of 130 consecutive patients scheduled for conventional coronary angiography were prospectively recruited in this study. Exclusion criteria included general contraindications to MR examination (claustrophobia, pacemaker), unstable angina, atrial fibrillation, patients with coronary stents or bypass grafts, and renal insufficiency (estimated glomerular filtration rate assessed by creatinine clearance <60 mL/min per 1.73 m²). Twenty patients were excluded for these reasons and 110 patients (54 men, age 58±11 years) underwent coronary MRA before conventional coronary angiography (Figure 1). The study protocol was approved by the institutional review board of our hospital. Written informed consent was obtained from each patient before the study.

Patient Preparation
A β-blocker (metoprolol tartrate, 25–50 mg) was given orally to patients with heart rate >75 bpm before coronary MRA. All images were collected under free breathing, with the patient in supine position. Patients were trained to perform shallow breathing during coronary MRA data acquisition. Abdominal belt was wrapped non-tightly in patients with irregular breathing pattern to suppress the vertical motion of the diaphragm.

Acquisition of 3.0T Whole-Heart Coronary MRA With 32-Channel Cardiac Coils
Contrast-enhanced whole-heart coronary MRA was performed on a 3.0T whole-body scanner (MAGNETOM Trio; Siemens AG Healthcare, Germany) with a 32-channel cardiac coil (Invivo, Gainesville, FL). The procedures were as follows: 2-dimensional (2D) scout images were first obtained in 3 orthogonal orientations to identify the position of the heart and diaphragm. Four-chamber view cine images were then acquired with a fast low-angle shot sequence during free breathing. The global cardiac motion was visually assessed from the cine images and patient-specific data-acquisition windows were determined either in the diastolic or systolic phase.

Free-breathing, contrast-enhanced coronary MRA was obtained using a ECG-triggered, navigator-gated, inversion-recovery prepared, segmented 3D fast low-angle shot sequence (repetition time/echo time=3.3/1.5 ms; TI=200 ms; flip angle=20°; readout bandwidth=700 Hz/pixel; voxel size=1.1x1.1x1.3 mm³ interpolated to 0.55x0.55x0.65 mm³) with slow infusion of 0.15 mmol/kg body weight of Gadobenate dimeglumine (MultiHance; Bracco Imaging SpA, Milan, Italy) at a rate of 0.3 mL/s. Sixty seconds after the initiation of contrast administration, data acquisition was started. Navigator echo signal was acquired from a 2D beam perpendicular to the right hemi-diaphragm. The width of navigator acceptance window was ±2.5 mm. The shift of 3D imaging volume was correlated to the shift of navigator tracking point using a prospective real-time adaptive motion correction with a constant (0.6) correction factor in the superior–inferior direction.11 Three-dimensional whole-heart coronary MRA scan was accelerated by using a combination of partial Fourier in the slab-encoding direction with a factor of 6/8 and generalized autocalibrating partially parallel acquisitions acceleration factor of 3 in the phase-encoding direction.

Conventional Coronary Angiography Studies
X-ray coronary angiography was performed in all patients and evaluated by quantitative coronary angiography (QuanCor QCA, Siemens Healthcare) by 2 cardiologists who were blinded to the coronary MRA results. Standard 15-segment American Heart Association classification system was used. Stenoses were quantitatively evaluated for segments with a reference diameter of ≥1.5 mm. Significant CAD was defined as a luminal diameter reduction of ≥50% in coronary arteries.

Contrast-Enhanced Whole-Heart Coronary MRA Image Analysis
Coronary MRA images were transferred to an external workstation (MMWP, Siemens AG Healthcare, Erlangen, Germany). Two experienced readers who were blinded to the patient information independently assessed coronary MRA using axial source images, curved multiplanar reformations, and thin-slab sliding maximum intensity projections images. Coronary MRA image quality was graded on a 4-point scale (1, nonassessable with severe image artifacts, poor vessel contrast; 2, assessable with moderate image artifacts, fair vessel contrast; 3, assessable with minor artifacts, good vessel contrast; 4, assessable with no apparent artifacts, excellent vessel contrast). The scores generated by 2 readers were averaged. Significant narrowing of the coronary arteries (≥50% reduction in diameter) was visually assessed by 2 observers. Each observer independently recorded the presence or absence of significant stenosis to determine the interobserver agreement of binary judgment. All coronary arteries were included for the evaluation regardless of the image quality of coronary MRA to avoid overestimation of the diagnostic accuracy. A consensus reading was performed for the segments in which there was disagreement between the 2 observers. Vessel-based data sets were constructed from the final segment data to generate the patient-based data sets.

Statistical Analysis
Sensitivity, specificity, positive predictive value, negative predictive value, and accuracy with 95% CIs were calculated on a per-segment, per-voxel, and per-patient basis using invasive x-ray coronary angiography as reference standard. The intention-to-read approach was used and nonassessable segments were considered to have a stenosis.
A vessel was considered diseased if it presented at least 1 segment with a coronary stenosis $\geq 50\%$, and a patient was considered as having CAD if he or she had at least 1 vessel with a $\geq 50\%$ stenosis.

The level of agreement between the 2 readers with respect to the image-quality grading was assessed by weighted $\kappa$ statistics. The interobserver agreement for the binary judgments for the presence or absence of stenosis was evaluated using $\kappa$ statistics. Number of cases without successfully coronary MRA was not taken into account in the calculation of diagnostic performance. All statistical analysis was performed using statistical software (SAS version 9.1, SAS Institute Inc. Cary, NC). Quantitative variables were expressed as mean value$\pm$SD, and categorical variables as percentages.

### Results

Coronary MRA was successfully completed in 101 of 110 (92%) patients without complications. Nine patient studies were aborted because of poor ECG signal (n=4), or extremely low respiratory gating efficiency (<20%, n=5). The characteristics of the study population are summarized in Table 1. The prevalence of having at least 1 significant coronary stenosis in patients with successful coronary MRA was 49%. Mean heart rate during coronary MRA was 66±8 bpm. Coronary MRA was acquired during diastole in 67% (68/101) (acquisition window 124±28 ms) and during systole in 33% (33/101) (acquisition window 84±6 ms). The average navigator acceptance rate was 36%.

### Image Quality of the Whole-Heart Coronary MRA

In 101 patients, a total of 403 vessels and 1181 coronary artery segments were evaluated. Of 1181 segments 1104 (93.5%) segments with a reference luminal diameter $\geq 1.5$ mm on QCA were evaluated as assessable (score 2–4). The reasons for 77 nonassessable segments were poor contrast-to-noise ratio (n=33), motion artifacts (n=29), and small diameter (n=15). The image score was 3.2±0.8. Weighted $\kappa$ value for interobserver agreement for image-quality grading was 0.86. The whole-heart coronary MRA image quality of 101 patients is summarized in Table 2.

## Table 1. Characteristics of the Study Population

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Patients Who Underwent Coronary MRA (n=110)</th>
<th>Patients With Successful Coronary MRA (n=101)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>58±11</td>
<td>58±11</td>
</tr>
<tr>
<td>Range, y</td>
<td>39–84</td>
<td>36–80</td>
</tr>
<tr>
<td>Sex, n male/female</td>
<td>54/46</td>
<td>48/53</td>
</tr>
<tr>
<td>Body mass index, kg/m²</td>
<td>24±3</td>
<td>24±3</td>
</tr>
<tr>
<td>Hypertension, n (%)</td>
<td>45 (41)</td>
<td>43 (47)</td>
</tr>
<tr>
<td>Hypercholesterolemia, n (%)</td>
<td>48 (44)</td>
<td>45 (45)</td>
</tr>
<tr>
<td>Diabetes mellitus, n (%)</td>
<td>28 (23)</td>
<td>26 (26)</td>
</tr>
<tr>
<td>Current or prior cigarette smoking, n (%)</td>
<td>45 (41)</td>
<td>42 (42)</td>
</tr>
<tr>
<td>Chest pain, n (%)</td>
<td>68 (62)</td>
<td>65 (64)</td>
</tr>
<tr>
<td>Prior myocardial infarction, n (%)</td>
<td>18 (16)</td>
<td>19 (19)</td>
</tr>
<tr>
<td>Stenosis on x-ray coronary angiography, n (%)</td>
<td>54 (50)</td>
<td>49 (49)</td>
</tr>
<tr>
<td>One vessel, n</td>
<td>25</td>
<td>21</td>
</tr>
<tr>
<td>Two vessels, n</td>
<td>19</td>
<td>18</td>
</tr>
<tr>
<td>Three vessels, n</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>$\beta$-blocker administered before scan, n (%)</td>
<td>27 (25)</td>
<td>23 (23)</td>
</tr>
<tr>
<td>Heart rate on coronary MRA, bpm</td>
<td>66±8</td>
<td>66±8</td>
</tr>
</tbody>
</table>

MRA indicates magnetic resonance angiography.

A vessel was considered diseased if it presented at least 1 segment with a coronary stenosis $\geq 50\%$, and a patient was considered as having CAD if he or she had at least 1 vessel with a $\geq 50\%$ stenosis. The level of agreement between the 2 readers with respect to the image-quality grading was assessed by weighted $\kappa$ statistics. The interobserver agreement for the binary judgments for the presence or absence of stenosis was evaluated using $\kappa$ statistics. Number of cases without successfully coronary MRA was not taken into account in the calculation of diagnostic performance. All statistical analysis was performed using statistical software (SAS version 9.1, SAS Institute Inc. Cary, NC). Quantitative variables were expressed as mean value$\pm$SD, and categorical variables as percentages.

## Table 2. Image Quality of 101 Patients With Successful CMRA

<table>
<thead>
<tr>
<th>No. of Segments $\geq 1.5$ mm on QCA</th>
<th>No. of Assessable Segments on CMRA (%)</th>
<th>Causes of Nonassessibility</th>
<th>Image Quality of CMRA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>101 (100)</td>
<td>Poor Opacification</td>
<td></td>
</tr>
<tr>
<td>LM</td>
<td>101</td>
<td>0</td>
<td>3.4±0.5</td>
</tr>
<tr>
<td>LAD Proximal</td>
<td>101</td>
<td>97 (96)</td>
<td>3</td>
</tr>
<tr>
<td>Mid</td>
<td>98</td>
<td>93 (95)</td>
<td>3</td>
</tr>
<tr>
<td>Distal</td>
<td>84</td>
<td>74 (88)</td>
<td>3</td>
</tr>
<tr>
<td>Diagonal branches</td>
<td>116</td>
<td>100 (86)</td>
<td>7</td>
</tr>
<tr>
<td>LCX Proximal</td>
<td>100</td>
<td>97 (97)</td>
<td>1</td>
</tr>
<tr>
<td>Distal</td>
<td>79</td>
<td>74 (94)</td>
<td>2</td>
</tr>
<tr>
<td>Marginal branches</td>
<td>111</td>
<td>99 (89)</td>
<td>4</td>
</tr>
<tr>
<td>RCA Proximal</td>
<td>101</td>
<td>101 (100)</td>
<td>0</td>
</tr>
<tr>
<td>Mid</td>
<td>101</td>
<td>101 (100)</td>
<td>0</td>
</tr>
<tr>
<td>Distal</td>
<td>94</td>
<td>91 (97)</td>
<td>2</td>
</tr>
<tr>
<td>PDA/PL</td>
<td>95</td>
<td>76 (80)</td>
<td>8</td>
</tr>
<tr>
<td>Total</td>
<td>1181</td>
<td>1104 (94)</td>
<td>33</td>
</tr>
</tbody>
</table>

CMRA indicates coronary magnetic resonance angiography; QCA, quantitative coronary angiography; LAD, left anterior descending coronary artery; LCX, left circumflex coronary artery; LM, left main coronary artery; RCA, right coronary artery; pro, proximal; mid, middle; dis, distal; PDA, posterior descending artery; and PL, posterior lateral.

Data are expressed as means$\pm$SD.
Diagnostic Performance of Coronary MRA Compared With QCA

3.0T contrast-enhanced whole-heart coronary MRA correctly identified significant CAD in 47 out of 49 patients and correctly ruled out CAD in 45 out of 52 patients (Figures 2 and 3). In all patients with left main or 3-vessel disease (100%, 11 of 11), coronary MRA detected at least 1 significant coronary stenosis, which means that on a per-patient basis all these patients were correctly identified. \( \kappa \) value for the binary judgment was 0.89 (95% CI, 0.80–0.98) on per-patient based analysis.

In a total of 1104 assessable coronary segments, QCA detected a total of 107 lesions (≥50%). Coronary MRA correctly identified 91 of these lesions. In 986 segments, stenosis was ruled out correctly by coronary MRA. A detailed overview of the diagnostic performance of 3.0T coronary MRA compared with that of QCA is summarized in Table 3.

Discussion

This prospective, single-center study demonstrated high diagnostic performance of 3.0T contrast-enhanced whole-heart coronary MRA using 32-channel cardiac coils in intermediate symptomatic patients for the detection of obstructive CAD. The patient-based sensitivity and specificity of whole-heart coronary MRA with 32-channel coils in the detection of significant stenoses were 95.9% and 86.5%, respectively. Thus, our data establish coronary MRA at 3.0T using a 32-channel cardiac coil as a robust technique to perform noninvasive and radiation-free coronary angiography.

To the best of our knowledge, this is the first study in which 32-channel cardiac coils, 3.0T MR imaging system, and highly accelerated parallel imaging were combined to perform whole-heart coronary MRA. A very recent study has investigated the use of 32-channel coils to perform whole-heart coronary MRA at 1.5T with high parallel imaging factors. In that study, substantially shortened imaging time and high...
study success rate were observed. Nevertheless, it is known that the straightforward application of parallel imaging at field strengths of 1.5T dramatically reduces acquisition time, but at the cost of signal-to-noise ratio. The baseline signal-to-noise ratio gain at 3.0T can be used to trade-off spatial and temporal resolution of coronary MRA with parallel imaging.13,14

In our study, whole-heart coronary MRA was obtained with a substantially reduced acquisition time (7.0±1.8 minutes) compared with previous studies without using 32-channel coils.15 Reduced acquisition time can be translated into an improvement of inplane and through-plane spatial resolution, which resulted in an improved delineation of distal segments of the coronary arteries. In most of the previous studies on coronary MRA, evaluation was limited to branches having a diameter >2 mm.15,16 We evaluated all segments being >1.5 mm in diameter, whereas only 6.5% of the coronary segments were nondiagnostic—significantly lower than findings of our previous study (12%).13 In addition, the time savings improve the clinical throughput of coronary MRA and potentially decrease patient discomfort resulting from long measurements. The resulting measurable improvements of coronary MRA using 32-channel cardiac coils in image quality are likely to translate into more stable, more diverse, and more widely accepted clinical applications.

Multislice CT has emerged as a rapid and noninvasive tool for the detection of CAD, and numerous methods for dose reduction have been developed recently.17,18 However, the penetration of these techniques into widespread clinical practice

Table 3. Accuracy of WH-CMRA Using 32-Channel Cardiac Coils for Detection of Coronary Stenosis

<table>
<thead>
<tr>
<th></th>
<th>Patient Based n=101</th>
<th>Vessel Based n=403</th>
<th>Segment Based n=1181</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sensitivity, % (95% CI)</td>
<td>95.9 (86.0–99.4)</td>
<td>88.7 (80.3–94.5)</td>
<td>85.1 (76.9–91.2)</td>
</tr>
<tr>
<td>Specificity, % (95% CI)</td>
<td>86.5 (74.2–94.4)</td>
<td>91.1 (87.9–93.4)</td>
<td>91.8 (90.0–93.4)</td>
</tr>
<tr>
<td>Positive predictive value, % (95% CI)</td>
<td>87.0 (75.1–94.6)</td>
<td>68.7 (59.4–77.0)</td>
<td>50.8 (43.3–58.4)</td>
</tr>
<tr>
<td>Negative predictive value, % (95% CI)</td>
<td>95.7 (85.4–99.4)</td>
<td>97.4 (95.2–98.7)</td>
<td>98.4 (97.4–99.1)</td>
</tr>
</tbody>
</table>

WH-CMRA indicates whole-heart coronary magnetic resonance angiography.
*Data are percentages, with raw data in parentheses and 95% CI.
has not yet established, and current guidelines recommend a heart rate of than 60 bpm both for optimal image quality and for reduction of radiation exposure.\textsuperscript{19} MR imaging is the most promising cardiac imaging test because of its unique advantage of not requiring radiation exposure, allowing concurrent assessment of myocardial structure, function, myocardial edema, fibrosis, and coronary arteries in a single setting. In our study only patients with heart rate >75 bpm received an oral β-blocker before the scan. Slow heart rates relatively prolong cardiac phases with little cardiac motion, so a data-acquisition window of patients with high heart rates can be safely set to allow artifact-free imaging. The high sensitivity (95.9\%) of coronary MRA for CAD shown in our study is comparable to the sensitivity of 64-slice CT studies performed in multicenter trials.\textsuperscript{1,20} The specificity (86.5\%) is on par with MR myocardial perfusion imaging, whereas the diagnostic sensitivity and negative predictive value are higher.\textsuperscript{21} The negative predictive value was 98.4\%, 97.4\%, and 95.7\% on per-segment, per-vessel, and per-patient basis, respectively, indicating that this technique can reliably rule out significant stenoses, which is consistent with findings from previous studies.\textsuperscript{7,15,16}

The low positive predictive value (50.8\%) on segment basis is explained for the most part by the nonassessable segments on coronary MRA. We did not exclude these segments from the analysis but tended to grade these lesions as having a significant obstruction. Our coronary stenosis grading policy is based on the premise that patients with either positive coronary MRA results or nonassessable segments will undergo QCA in an intention-to-read approach. Because of this, coronary MRA is not ready to challenge invasive coronary angiography as a true alternative.

Nevertheless, developments in parallel imaging\textsuperscript{22,25} and multichannel phased-array coils may further reduce the imaging time,\textsuperscript{24,25} this will have a considerable impact on improving spatial resolution and image quality because of inconsistent cardiac and respiratory motion. Thus, if the diagnostic performance of coronary MRA can be further improved, this test may become the most important imaging tool for noninvasively and comprehensively assessing patients with suspected CAD. Whole-heart coronary MRA at 3.0T has great potential to become a valuable complement to other noninvasive imaging modalities if current limitations, such as navigator failure rate and low spatial resolution, can be overcome.

There are several limitations that need to be acknowledged in this study. First, the capability to perform cardiac function, perfusion, and viability, as well as coronary imaging in the same setting for a comprehensive exam of CAD is a major strength of cardiac MR imaging. The need for contrast agent in both coronary MRA and cardiac perfusion scans will either lead to increased total contrast dose, or decreased dose from optimal value for coronary MRA or perfusion scans. The performance of coronary MRA with further reduced contrast dose is not yet established. Second, coronary MRA could not be acquired from ≈8\% of the patients because of unstable breathing patterns or poor ECG signal. Not including all subjects may result in overestimation of the diagnostic accuracy of coronary MRA.

Future studies are needed to define the method’s precise role in the diagnostic algorithm for the evaluation of patients with suspected CAD in multicenter trials. Third, despite the use of partial Fourier acquisition and parallel imaging, it is desirable to further improve the imaging speed with advanced acceleration and reconstruction techniques without compromising image quality. Finally, to acquire consistent coronary MRA images requires highly attentive and experienced operators on the setting of timing and imaging parameters. Broader utilization and acceptance of coronary MRA could be improved by simplifying or automating the protocol settings.

In conclusion, among patients who were scheduled to obtain conventional x-ray coronary angiography, we found that coronary MRA at 3.0T using 32-channel cardiac coils demonstrates high accuracy for detection of significant coronary artery stenosis. The high negative predictive value (97.5\%) establishes coronary MRA as an effective, noninvasive method to rule out significant coronary artery stenosis without exposure to ionizing radiation. The speed advantage and extra diagnostic value afforded by 32-channel cardiac coils at 3.0T may be expected to drive future technological developments of more robust and reliable coronary MRA.

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Coronary imaging with magnetic resonance has historically been challenging, but recent technical advantages may overcome prior limitations to reliable detection of coronary artery stenosis. This study evaluated whole-heart navigator-gated, ECG-triggered and free-breathing coronary magnetic resonance angiography acquired after intravenous infusion of gadolinium-based contrast successfully performed in 101 patients also undergoing traditional invasive x-ray angiography. Magnetic resonance angiography acquisition time averaged 7.0±1.8 minutes. For a cutoff of 50% luminal stenosis by quantitative coronary angiography with whole-heart navigator-gated, electrocardiogram-triggered high-pitch spiral acquisition. J Am Heart J. 2010;3:340–346.


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