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3.0T Whole-Heart Coronary Magnetic Resonance Angiography Performed with 32-Channal Cardiac Coils: A Single Center Experience:

Yang et al: 3T Whole-Heart Coronary MR Angiography with 32-Channel Coils

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Abstract

Background—Whole-heart coronary MR angiography (MRA) is a promising method for non-invasive, radiation-free detection and exclusion of obstructive coronary artery disease (CAD); 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-channal 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 CAD referred for clinically indicated conventional coronary angiography were included in this prospective study. 32-channel receiver coils were used for 3.0T coronary MRA data acquisition. An ECG-triggered, navigator-gated, inversion-recovery prepared, segmented gradient-echo sequence was used for image acquisition with an acceleration factor of three in the phase-encoding direction using GRAPPA reconstruction. Acquisition of coronary MRA was successfully completed in 101 of 110 (92%) patients with average imaging time of 7.0 ± 1.8 min. 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% to 99.4%), 86.5% (45/52, 95% CI, 74.2% to 94.4%), 87.0% (47/54, 95% CI, 75.1% to 94.6%) and 95.7% (45/47, 95% CI, 85.4% to 99.4%), respectively.

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Disclosures

Dr Kuncheng reported receiving honoraria for lectures from Siemens Medical Systems and Bracco.

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

Clinical Trial Registration—URL: <http://www.chictr.org>. Unique identifier: ChiCTR-DDT-07000121.

Keywords

magnetic resonance angiography; coronary arteries; 3.0 T

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 multi-slice CT (MSCT), non-invasive 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 concern³. Over the past 15 years, the continuous improvement in MRI technology allows non-invasive, radiation-free, comprehensive evaluation of CAD⁴⁻⁶. Initial experiences have shown that the diagnostic accuracy of contrast-enhanced whole-heart coronary MRA at 3.0T in detecting coronary artery stenosis approaches that of 64-slice CT⁷. Nevertheless, coronary MR angiography (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 recently with the novel multi-channel cardiac coils and high parallel imaging factors¹⁰. 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.

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

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/1.73 m²). 20 patients were excluded for these reasons and 110 patients (54 men, age 58 ± 11) 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 prior to the study.

Patient Preparation

A beta-blocker (metoprolol tartrate, 25 to 50 mg) was given orally to patients with heart rate >75 beats/min 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 breath 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, Florida, USA). The procedures were as follows: Two dimensional (2D) scout images were first obtained in three 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 (FLASH) 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 FLASH sequence (TR /TE = 3.3/1.5 ms; TI = 200 ms; flip angle = 20°; readout bandwidth = 700 Hz/pixel; voxel size = 1.1 × 1.1 × 1.3 mm³ interpolated to 0.55 × 0.55 × 0.65 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/sec. 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 direction¹¹. 3D 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 (GRAPPA) 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 (QuantCor QCA, Siemens Healthcare) by two cardiologists who was 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 or more. Significant coronary artery disease 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 (CPR), and thin-slab sliding maximum intensity projections (MIP) images. Coronary MRA image quality was graded on a 4-point scale (1, non-assessable 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 two readers were averaged. Significant narrowing of the coronary arteries (> 50% reduction in diameter) was visually assessed by two 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 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 two 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 (PPV), negative predictive value (NPV), and accuracy with 95% confidence intervals were calculated on a per-segment, per-vessel and per-patient basis using invasive x-ray coronary angiography as reference standard. The intention-to-read approach was used and non-assessable 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 two 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, North Carolina, USA). Quantitative variables were expressed as mean value \pm standard deviation, and categorical variables as percentages.

Results

Coronary MRA was successfully completed in 101 of 110 (92%) patients without complications. Nine patient studies were aborted due to 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 one significant coronary stenosis in patients with successful coronary MRA was 49%. Mean heart rate during coronary MRA was 66 ± 8 beats/min. 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. 1104 of 1181 (93.5%) segments with a reference luminal diameter ≥ 1.5 mm on QCA were evaluated as assessable (score 2 to 4). The reasons for 77 non-assessable 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.

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 (Figure 2, 3). In all patients with left main or 3-vessel disease (100%, 11 of 11), coronary MRA detected at least one significant coronary stenosis, which means that on a per-patient basis all of 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 ($\geq 50\%$). 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 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 MRI 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 factors¹². In their 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 SNR. The baseline SNR gain at 3.0T can be used to tradeoff 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 min) compared to previous studies without using 32-channel coils¹⁵. Reduced acquisition time can be translated into an improvement of in-plane and through-plane spatial resolution, which resulted in an improved delineation of distal segments of the coronary arteries. In most of the previous coronary MRA studies, evaluation was limited to branches having a diameter >2 mm^{15, 16}. We evaluated all segments being >1.5 mm in diameter, while only 6.5% of the coronary segments were non-diagnostic, significantly lower than findings of our previous study (12%)⁷. In addition, the time savings improves 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.

MSCT 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 has not yet established, and current guidelines recommend a heart rate of than 60 beats per minute both for optimal image quality and for reduction of radiation exposure¹⁹. MRI is the most promising cardiac imaging test due to 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 higher than 75 beats per minute received an oral beta-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^{1, 20}. The specificity (86.5%) is on par with magnetic resonance myocardial perfusion imaging, whereas the diagnostic sensitivity and NPV are higher²¹. The NPV 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, consistent with findings from previous studies^{7, 15, 16}.

The low PPV (50.8%) on segment basis is explained for the most part by the non-assessable 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 non-assessable 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^{22, 23} and multi-channel phased-array coils may further reduce the imaging time^{24, 25}, this will have a considerable impact on improving spatial resolution and image quality due to 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 non-invasive 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. 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 and/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 about 8% of the patients due to 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 multi-center 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 3.0 T using 32-channel cardiac coils demonstrates high accuracy for detection of significant coronary artery stenosis. The high NPV (95.8%) 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 3.0 T may be expected to drive future technological developments of more robust and reliable coronary MRA.

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Abbreviations

CT computed tomography

MRI	magnetic resonance imaging
SNR	signal-to-noise ratio
FLASH	fast low-angle shot
GRAPPA	Generalized auto calibrating partially parallel acquisitions
LM	left main coronary artery
LAD	left anterior descending coronary artery
LCX	left circumflex coronary artery
RCA	right coronary artery
QCA	quantitative coronary angiography
SSFP	steady-state free precession
RF	radio-frequency
TR	repetition time
TE	echo time

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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 (MRA) acquired after intravenous infusion of gadolinium-based contrast successfully performed in 101 patients also undergoing traditional invasive x-ray angiography. MRA acquisition time averaged 7.0 ± 1.8 min. For a cutoff of 50% luminal stenosis by quantitative coronary angiography, 3D-MRA performed well with positive and negative predictive values averaging 87.0 and 95.7%, respectively. With contemporary techniques, coronary MRA can be performed efficiently, and warrants greater consideration as a suitable noninvasive method to exclude obstructive coronary artery disease.

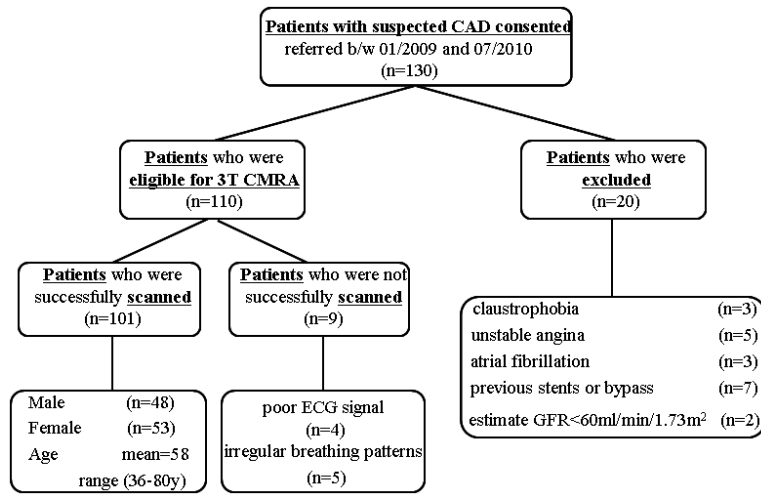


Figure 1. Flow Diagram of Patient Recruitment

CAD = Coronary Artery Disease. 32-CC Coronary MRA = 32 channel cardiac coils coronary MRA.

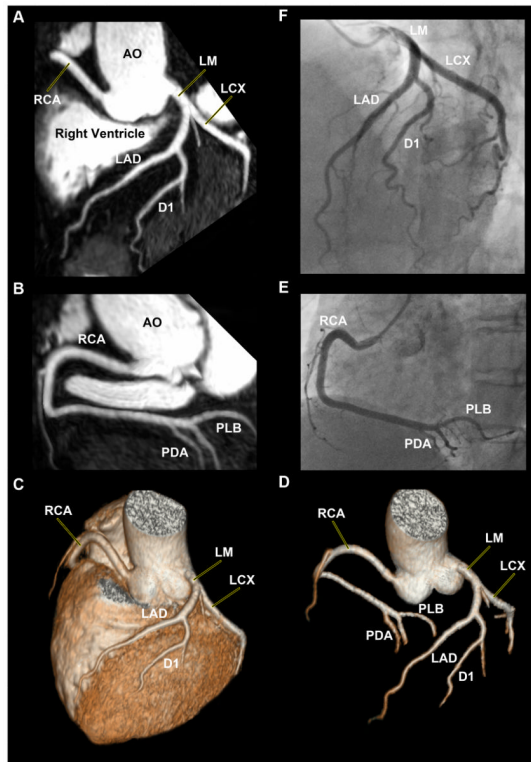


Figure 2. 32-Channel Cardiac Coils Based Whole-Heart Coronary MR Angiography Exclusion of Significant Coronary Artery Disease (Imaging time: 4 min 14 sec)

Left anterior oblique image reformatted with curved multiplanar reformation depicts LM, LAD, LCX and the first diagonal branch (A), right anterior oblique image reformatted with curved multiplanar reformation shows RCA, posterior descending artery (PDA), and posterior lateral branch (PLB) (B). Volume-rendered image provides an overview of coronary anatomy (C). Better visualization of the entire coronary artery tree after removing the background of myocardium, long segments of all major coronary arteries are well depicted (D). The conventional coronary angiography confirms the absence of significant coronary artery disease (E, F). AO = aorta, LM = left main coronary artery, OM = obtuse marginal branch, D1 = first diagonal branch, D2 = second diagonal branch, LCX = left circumflex coronary artery, RCA = right coronary artery.

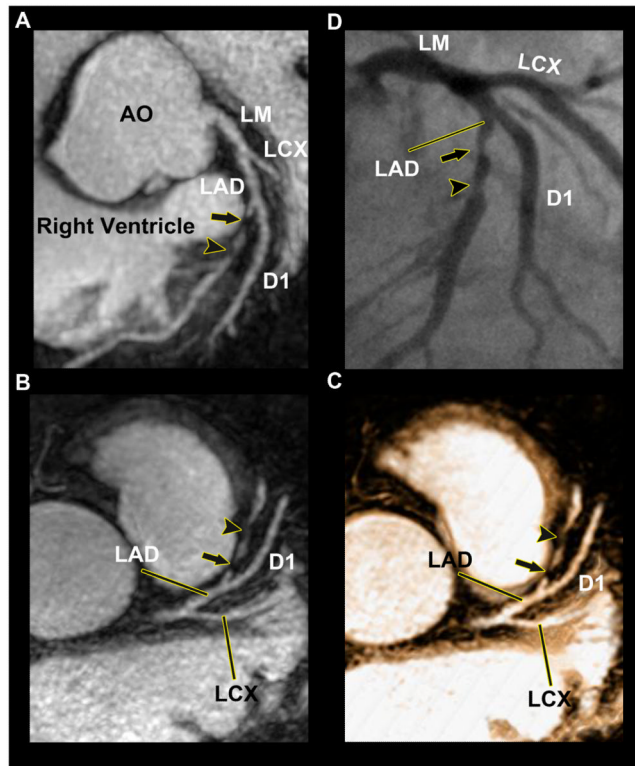


Figure 3. 32-Channal Cardiac Coils Based Whole-Heart CMRA Image of the LAD With Significant Coronary Artery Disease (Imaging time: 3 min 34 sec)
 Sliding thin-slab maximum intensity projection images (A, B) and the thin-slab volume-rendered image (C) disclose a significant coronary stenosis (arrow) and distally an intermediate coronary stenosis (arrowhead) in the mid LAD, which were both corroborated by conventional coronary angiography (B). Abbreviations as in Figures 2.

Table 1

Characteristics of the study population

Characteristics	Patients Who Underwent Coronary MRA (n =110)	Patients With Successful Coronary MRA (n =101)
Age, yrs	58±11	58±11
Range	39-84	36-80
Sex, male/female	54 / 46	48 / 53
Body mass index (kg/m ²)	24±3	24±3
Hypertension, n (%)	45 (41%)	43(47%)
Hypercholesterolemia, n (%)	48(44%)	45 (45%)
Diabetes mellitus	28(23%)	26(26%)
Current or prior cigarette smoking, n (%)	45 (41%)	42(42%)
Chest pain	68(62%)	65 (64%)
Prior myocardial infarction	18 (16%)	19 (19%)
Stenosis on x-ray coronary angiography	54 (50%)	49 (49%)
One vessel	25	21
Two vessel	19	18
Three vessel	10	10
Beta-blocker administered before scan	27 (25%)	23 (23%)
Heart rate on coronary MRA, beats/min	66±8	66±8
Range	51-88	51-88

Table 2

Image quality of 101 patients with successful CMRA

	No. of Segments 1.5 mm On QCA	No. of Assessable Segments on CMRA	Causes of Nonassessability			Image Quality of CMRA
			Poor opacification	Motion artifacts	Small caliber	
LM	101	101(100%)	0	0	0	3.4 ± 0.5
LAD						
Proximal	101	97(96%)	3	1	0	3.3 ± 0.7
Mid	98	93(95%)	3	2	0	3.3 ± 0.8
Distal	84	74(88%)	3	5	2	3.1 ± 1.0
Diagonal branches	116	100(86%)	7	4	5	3.1 ± 1.0
LCX						
Proximal	100	97(97%)	1	2	0	3.3 ± 0.7
Distal	79	74(94%)	2	2	1	3.2 ± 0.8
Marginal branches	111	99(89%)	4	5	3	2.9 ± 1.0
RCA						
Proximal	101	101 (100%)	0	0	0	3.4 ± 0.5
Mid	101	101 (100%)	0	0	0	3.4 ± 0.5
Distal	94	91(97%)	2	1	0	3.3 ± 0.7
PDA/PL	95	76(80%)	8	7	4	2.8 ± 1.1
Total	1181	1104(94%)	33	29	15	3.2 ± 0.8

Data are expressed as means ± SD. 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.

Table 3

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

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

Abbreviations: CI, confidence interval.

* Note.—Data are percentages, with raw data in parentheses and 95% confidence