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Noninvasive Detection of Coronary Artery Stenoses with Multislice Computed Tomography or Magnetic Resonance Imaging

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Background: Multislice computed tomography (CT) and magnetic resonance imaging (MRI) are the main candidates for noninvasive coronary angiography; however, multislice CT, unlike MRI, exposes patients to radiation and an iodinated intravenous contrast agent.

Objective: To compare the diagnostic accuracy of multislice CT and MRI for noninvasive detection of clinically significant coronary stenoses (≥50%).

Design: Prospective intention-to-diagnose study.

Setting: Single tertiary referral center, Berlin, Germany.

Patients: 129 consecutive patients with suspected coronary artery disease.

Interventions: Multislice CT and MRI were both performed within a median of 1 day before conventional coronary angiography, which served as the reference standard.

Measurements: Diagnostic performance of multislice CT and MRI.

Results: 129 patients completed the study. Altogether, 108 patients with 430 vessels could be examined with both multislice CT and MRI and were used for analysis. In the per-patient analysis, the sensitivity of multislice CT (92% [95% CI, 82% to 96%]) was significantly higher than that of MRI (74% [CI, 61% to 83%]; $P = 0.013$). The sensitivity for detecting clinically significant stenoses was 82% for multislice CT and 54% for MRI ($P < 0.001$). Specificity and negative predictive value of multislice CT and MRI in the per-vessel analysis were 90% versus 87% ($P = 0.73$) and 95% versus 90% ($P = 0.032$), respectively. The effective radiation dose used with multislice CT (mean, 12.3 mSv [SD, 1.4]) in a consecutive subgroup of 73 patients was not significantly different from that used with diagnostic cardiac catheterization (11.4 mSv [SD, 4.8]) ($P = 0.169$). Most patients (74%) indicated that they would prefer multislice CT for future diagnostic imaging ($P < 0.001$).

Limitations: This was a single-center study with 129 patients.

Conclusions: In patients referred for conventional coronary angiography, multislice CT compares favorably with MRI for noninvasive detection of coronary stenoses.

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Coronary artery disease is a major public health issue, affecting 13.2 million persons in the United States and causing more than 500 000 deaths each year (1, 2). Diagnostic cardiac catheterization is performed more than 1.3 million times per year in U.S. hospitals (2) and is the best method available for detection of coronary stenoses; however, it is invasive and not without risk (3). Moreover, approximately 66% of all conventional coronary angiographies performed in Germany are for diagnostic purposes only and include no interventional procedure (4). From both the patient's point of view and a socioeconomic perspective, a noninvasive, painless, and cost-effective diagnostic approach that reduced the need for cardiac catheterization would be an important advance.

Two techniques, multislice computed tomography (CT) and magnetic resonance imaging (MRI), have been investigated for this purpose. In recent studies, multislice CT has been reported to be fairly accurate in the diagnosis of coronary artery disease (5–10), while a multicenter study has shown that MRI of the coronary arteries permits diagnosis of left main coronary artery stenoses and exclusion of 3-vessel disease (11). The results of these studies have implied that the diagnostic accuracy of multislice CT might be superior to that of MRI. However, multislice CT, unlike MRI, involves the use of radiation and intravenous administration of a contrast agent; thus, it should be recommended only if shown to provide superior diagnostic accuracy. We therefore conducted a prospective study to compare the diagnostic performance of multislice CT and MRI in a consecutive series of patients scheduled to undergo conventional coronary angiography. This intraindividual design made it possible to compare the tests in the same patients (12) and to analyze whether multislice CT and MRI complement each other.

METHODS

Study Design

The study was a single-institution comparison of the diagnostic performance of multislice CT and MRI for the detection of coronary artery stenoses in a prospective patient cohort, with quantitative coronary angiography as the reference standard. All patients and all coronary arteries

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Context

A negative result on a noninvasive coronary artery imaging test could reduce the need for coronary angiography.

Contribution

The authors did 3 coronary artery imaging tests—multislice computed tomography (CT), magnetic resonance imaging (MRI), and conventional radiography (the reference standard)—in 108 patients with clinically suspected coronary artery disease (CAD). The likelihood ratios for positive test results were 14.4 for multislice CT and 18.8 for MRI. For negative test results, they were 0.08 for multislice CT and 0.16 for MRI.

Implications

These tests' potential value is to rule out CAD. Multislice CT is superior to MRI for this purpose, but neither test reliably excludes CAD if the pretest odds are high, as in typical angina pectoris.

—The Editors

were included in each analysis, even if a study or a vessel was not interpretable (that is, an intention-to-diagnose design was used). By using this design, we could avoid overestimating diagnostic accuracy (12–14). All 25 criteria of the Standards for Reporting of Diagnostic Accuracy (STARD) statement (13) can be found in this report. Multislice CT and MRI were both performed before conventional coronary angiography to avoid differential verification bias (15). The study protocol was approved by the institutional review board and the responsible federal authority (Federal Department for Radiation Protection).

Study Group

The study group consisted of consecutive eligible patients who were referred to our institution in Berlin, Germany, by outpatient centers and scheduled to undergo conventional coronary angiography within 14 days for clinically suspected coronary artery disease based on symptoms or results of diagnostic tests (for example, treadmill exercise test, myocardial scintigraphy, and echocardiography). Patients were eligible for the study if they were at least 40 years of age and were in sinus rhythm. As in previous studies (5–11), sinus rhythm was an inclusion criterion because a regular heartbeat is currently required for consistent successful application of noninvasive coronary imaging. The age limit of 40 years was set by the Federal Department for Radiation Protection because younger patients have increased susceptibility to ionizing radiation. The exclusion criteria were previous conventional coronary angiography, unstable angina or acute myocardial infarction, coronary artery bypass graft or stent, pregnancy or breastfeeding, or orthopnea. Patients were also excluded if they were under guardianship at the time of the study. Patients with contraindications to MRI (pacemaker, severe claustrophobia, or intracranial or intra-auricular metallic implants) or multislice CT (renal insufficiency [creatinine level $\geq$132.6 μmol/L ($\geq$1.5 mg/dL)] or allergy to iodinated contrast agents) were not examined with the contraindicated method and were excluded from the analysis. Enrollment took place between 5 November 2003 and 16 September 2004. All patients gave written informed consent. If no contraindications to nitroglycerine (such as aortic stenosis) were present, each patient received sublingual isosorbide dinitrate (5 mg) immediately before multislice CT and MRI. Sixty-five patients undergoing multislice CT were receiving long-term oral β-blocker therapy, but no additional oral or intravenous β-blockers were given before CT because such therapy might have favored CT over MRI (a negative correlation has been shown between heart rate and image quality for multislice CT [16]).

Multislice CT Protocol

Imaging was performed during 1 breath-hold by using a 16-slice CT scanner with 0.5-mm detector collimation (Aquilion 16, Toshiba Medical Systems, Otawara, Japan), as described elsewhere (17), after intravenous injection of a nonionic, iso-osmolar contrast agent (iodixanol, 320 mg of iodine per mL [Visipaque, GE Healthcare Biosciences, Buckinghamshire, United Kingdom]) at a rate of 3.5 mL/s. Further details of the multislice CT protocol are given in the Appendix (available at www.annals.org).

MRI Protocol

Magnetic resonance imaging was performed on a 1.5-T system (Magnetom Sonata, Siemens Medical Solutions, Erlangen, Germany) equipped with a high-performance gradient subsystem (maximum amplitude, 40 mT/m, and minimum rise time, 200 microseconds) using a dedicated cardiac 12-element phased-array coil as described recently (18). Further details of the MRI protocol are given in the Appendix (available at www.annals.org).

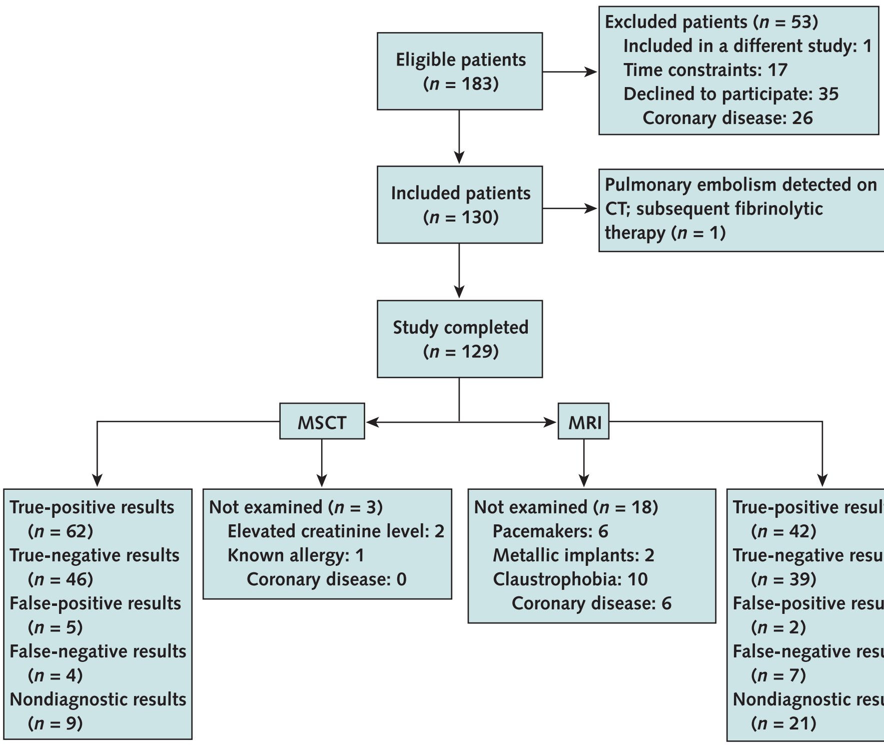
Conventional Coronary Angiography

Selective coronary angiography was performed with the transfemoral Judkins approach by using standard techniques after right and left intracoronary administration of 100 to 150 μg of isosorbide dinitrate.

Interpretation of Imaging Results

Multislice CT and magnetic resonance angiograms were processed and interpreted independently in random order by 2 readers on a workstation (Vitrea 2, version 3.3, Vital Images, Plymouth, Minnesota) in a blinded fashion, without knowledge of the results of conventional coronary angiography and clinical characteristics. For multislice CT, all 15 coronary artery segments (according to the classification of the American Heart Association; see the Appendix Figure, available at www.annals.org) (19) constituted the basis for evaluation. In contrast, for MRI only the 8 proximal and middle segments, namely segments 1, 2, and 3 (of the right coronary artery); segment 5 (the left main coronary artery); segments 6 and 7 (of the left anterior descending coronary artery); and segments 11 and 13 (of the left circumflex

Figure 1. **Flow diagram of patient recruitment and examination according to the Standards for Reporting of Diagnostic Accuracy statement.**



Per-patient results are presented according to findings of conventional coronary angiography by using all 15 coronary artery segments for multislice computed tomography (*MSCT*) and only the 8 proximal and middle segments for magnetic resonance imaging (*MRI*). Adapted from Bossuyt et al. (13). CT = computed tomography.

coronary artery) were evaluated because the limited spatial resolution of MRI does not allow detection of coronary stenoses in distal segments and side branches (11). With axial slices, 3-dimensional reconstructions, and curved multiplanar reformations, all coronary arteries were classified quantitatively as having clinically significant disease (≥50% diameter reduction) or no significant disease (<50%) on multislice CT by using a semiautomatic vessel analysis tool (17) and on MRI by using visual quantification as described elsewhere (18). Coronary arteries that could not be adequately interpreted because of poor image quality were classified as not interpretable.

Quantitative analysis of the coronary angiograms (Integris 3000, Philips Medical Systems, Best, the Netherlands) was performed by an experienced reader without knowledge of the results of multislice CT and MRI. At least 2 orthogonal projections were evaluated; the measurement was performed in the projection that showed the highest degree of stenosis. The diameter of the reference vessel on conventional coronary angiography had to measure at least 1.5 mm for a stenosis to be included in the analysis, thus covering all stenoses that might be targets for revascularization (20).

Secondary Outcomes

The total room time required for each diagnostic method and the amount of contrast agent administered for multislice CT and conventional coronary angiography were secondary outcomes. In a consecutive subgroup of 73 patients, we compared effective radiation doses for multislice CT (21) and cardiac catheterization based on dose-area product measurements with a conversion factor of 0.22 for cGy · cm^2 (to mSv), excluding radiation necessary for interventions. Interobserver variability was measured by using the Cohen κ statistic. The patients were observed and questioned about adverse events at the time of each test and were instructed to report any symptoms during the entire in-hospital period. Before imaging, patients were informed that maximum subjective pain levels during all examinations would be assessed. After all tests had been performed, pain levels were measured by using visual analogue scales (horizontal, unmarked, 10 cm in length). Patients were asked to report their preference for 1 of the 3 imaging procedures ("Assume you would have to undergo coronary angiography again—which of the tests would you prefer?").

Table 1. **Characteristics of the 129 Patients with Suspected Coronary Artery Disease Who Completed the Study**

Characteristic	Value
Mean age, *y*	64 (SD, 8)
Men, *n (%)*	95 (74)
Hyperlipidemia, *n (%)*	66 (51)
Arterial hypertension, *n (%)*	93 (72)
Diabetes mellitus, *n (%)*	21 (16)
Clinical presentation, *n (%)*	
Typical angina	61 (47)
Atypical angina	32 (25)
Nonspecific chest pain	13 (10)
No chest pain	23 (18)
Previous myocardial infarction, *n (%)*	22 (17)
ST–T-wave changes, *n (%)*	24 (19)
Mean body mass index, *kg/m²*	27.0 (SD, 3.5)
Current cigarette smoking, *n (%)*	30 (23)
Mean heart rate during noninvasive imaging, *beats/min**	
Multislice computed tomography	70 (SD, 11)
Magnetic resonance imaging	70 (SD, 12)
Findings on conventional coronary angiography, *n (%)*†	
No clinically significant disease	62 (48)
1-Vessel disease	17 (13)
2-Vessel disease	26 (20)
3-Vessel disease	23 (18)
4-Vessel disease	1 (1)
Prevalence of clinically significant disease	67 (52)

* Heart rates during multislice computed tomography and magnetic resonance imaging were not significantly different.
† Based on assessment of all 15 coronary segments.

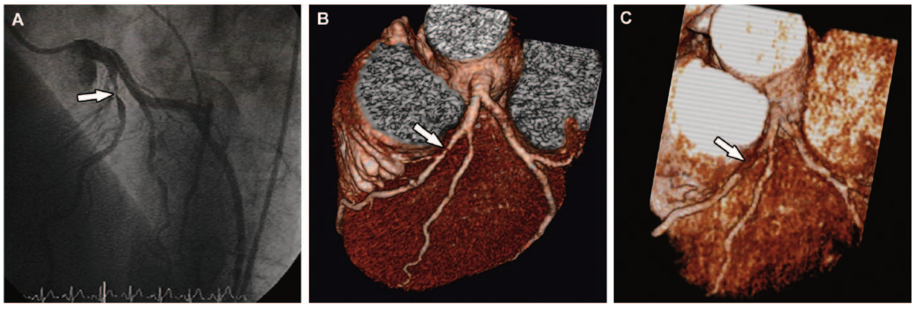
Statistical Analysis

The results of conventional coronary angiography served as the reference standard for assessing the sensitivity, specificity, and negative and positive predictive values of multislice CT and MRI, analyzed both per coronary artery and per patient. We included uninterpretable results in the calculation of sensitivity and specificity (as false-negative and false-positive results, respectively) by using a 6-cell matrix as described elsewhere (22, 23). Since the composition of a population influences sensitivity, specificity, and predictive values, we also calculated likelihood ratios. If a coronary artery contained more than 1 clinically significant stenosis, the most proximal significant stenosis by conventional angiography was used as the anatomic basis for analysis of that vessel because restricted flow resulting from proximal stenosis can limit accurate assessment of distal stenoses on noninvasive imaging (5). To calculate sample size before beginning the study, we assumed a per-patient diagnostic accuracy of 90% for multislice CT (5, 6) and 70% for MRI (11, 24), and a negative predictive value of 97% for multislice CT in the per-vessel analysis (5). We intended to give 80% power to the study, chose an α level of 0.025 (the usual α level of 0.05 corrected for the 2 planned primary outcomes according to the Bonferroni method), and used nQuery Advisor, version 4.0 (Statistical Solutions, Saugus, Massachusetts), with the chi-square test assuming unclustered data for analysis as described elsewhere (25). A sample size of 85 patients was calculated for the comparison of per-patient diagnostic accuracy of multislice CT and MRI. To demonstrate a per-vessel negative predictive value of multislice CT significantly greater than 90% at an expected value of 97%, 263 negative vessels were necessary. Thus, at an assumed maximum per-vessel event rate of 50% (wherein event equals stenosis), approximately 520 coronary vessels equal to a sample size of 130 patients were needed.

In the primary analysis, all 15 coronary segments were included for assessment of the diagnostic performance of multislice CT, but only the proximal and middle 8 segments were included in the analysis for MRI (as explained previously in the section on interpreting imaging results). In an additional analysis, all 15 segments were included for both multislice CT and MRI comparisons, with the 7 distal segments classified as negative on MRI if no stenosis was seen with MRI in these segments. If stenosis was seen in a distal segment with MRI, this segment was considered positive on MRI.

Nonparametric analysis for repeated measurements (26) was applied for per-vessel analysis to account for clustering of arteries within each patient by using a 2-factor

Figure 2. **Stenosis of the left anterior descending coronary artery in a 43-year-old man with typical angina.**



A. Stenosis on the conventional angiogram (*arrow*). B and C. Stenosis on 3-dimensional reconstructions obtained from multislice computed tomography and magnetic resonance imaging, respectively.

Table 2. **Direct Comparison of Test Results in 108 Patients***

Test Result	Result on Conventional Coronary Angiography, *n*		Likelihood Ratio (95% CI)†
	Positive	Negative	
Multislice CT			
Positive	56	3	14.4 (4.8–43.1)
Negative	4	37	0.08 (0.03–0.22)
Not interpretable‡	1	7	0.11 (0.01–0.86)
Total	61	47	
MRI §			
Positive	42	2	18.8 (4.8–73.7)
Negative	7	38	0.16 (0.08–0.34)
Not interpretable‡	8	11	0.65 (0.28–1.49)
Total	57	51	
MRI ‖			
Positive	42	2	16.2 (4.1–63.5)
Negative	10	35	0.22 (0.12–0.4)
Not interpretable‡	9	10	0.69 (0.31–1.57)
Total	61	47	

* CT = computed tomography; MRI = magnetic resonance imaging.
† Likelihood ratios are reported with 95% CIs for unclustered data as described elsewhere (27).
‡ Patients whose results were not interpretable were considered nondiagnostic for statistical analysis.
§ Using only the 8 proximal and middle coronary segments for MRI. Consequently, fewer patients had a positive conventional coronary angiogram for the MRI analysis than for the CT analysis.
‖ Using all 15 coronary segments for MRI as performed for multislice CT.

design (first factor, modality; second factor, vessel). Tests of significance for the per-patient analysis included the chi-square test (or Fisher exact test) and the McNemar test as appropriate. The *t*-test and the chi-square test were used for normally distributed and categorical secondary outcomes data, respectively. All data are reported as means with SDs, medians, or proportions with 95% CIs. For unclustered data (per-patient analysis), CIs for single proportions and differences of proportions were obtained by using the score method as described elsewhere (27, 28). For the per-vessel analysis, we corrected the variance inflation due to clustering by using the ratio estimator (29) as described for single (30) and paired (31) proportions. Because no correction formula for the variance of likelihood ratios exists, we used the bootstrap resampling technique (32) with 2500 replications to obtain lower and upper confidence bounds with the percentile method in the per-vessel analysis (33). Statistical analyses were conducted by using SPSS, version 12.0 (SPSS, Inc., Chicago); SAS, version 8.0 (SAS Institute, Inc., Cary, North Carolina); and StatXact, version 6.0 (Cytel Software Corp., Cambridge, Massachusetts). The CIs for clustered data were calculated by using our own program, written in R (34).

Role of the Funding Source

The funding source had no role in the collection, analysis, or interpretation of the data or in the decision to submit the manuscript for publication.

RESULTS

During the study period, 183 patients were eligible for inclusion. Of these, 1 patient was excluded because of previous enrollment in another study, 35 declined to participate, and 17 had to be excluded because of time constraints before planned coronary angiography. Of the 130 remaining patients, 1 was found on multislice CT to have pulmonary embolism; thus, study participation was discontinued. After exclusions, 129 patients completed the study (Figure 1).

Table 1 lists the characteristics of the 129 patients. Of these patients, 52% (67 of 129) had clinically significant coronary artery disease, 45% (58 of 129) were older than 65 years, and 16% (21 of 129) had a body mass index of at least 30 kg/m^2. In 1 patient, no left circumflex coronary artery was present, and another patient had no left main coronary artery. Three patients could not undergo multislice CT because of renal dysfunction or allergy to iodinated contrast agents. Eighteen patients could not be examined with MRI because of pacemakers, metallic implants, or claustrophobia (Figure 1). To minimize bias, only the 108 patients who could be examined with both multislice

Table 3. **Direct Comparison of Test Results in 430 Coronary Arteries***

Test Result	Result on Conventional Coronary Angiography, *n*		Likelihood Ratio (95% CI)†
	Positive	Negative	
Multislice CT			
Positive	110	12	20.25 (12.35–44.72)
Negative	15	265	0.13 (0.07–0.19)
Not interpretable‡	9	19	1.05 (0.36–2.48)
Total	134	296	
MRI §			
Positive	60	7	24.34 (12.45–84.16)
Negative	30	278	0.31 (0.22–0.40)
Not interpretable‡	22	33	1.89 (1.10–3.16)
Total	112	318	
MRI ‖			
Positive	61¶	7	19.25 (9.84–65.46)
Negative	44	263	0.37 (0.28–0.47)
Not interpretable‡	29	26	2.46 (1.44–4.34)
Total	134	296	

* CT = computed tomography; MRI = magnetic resonance imaging.
† Because no correction formula for the variance of likelihood ratios exists, we used the bootstrap resampling technique (32) to obtain lower and upper confidence bounds with the percentile method (33).
‡ Coronary arteries in patients who could not be examined were excluded from the analysis, and arteries that were not interpretable were considered nondiagnostic for statistical analysis.
§ Using only the 8 proximal and middle coronary segments. Consequently, a coronary artery with a single stenosis in a distal segment was considered negative for comparison of conventional coronary angiography with MRI.
‖ Using all 15 coronary segments for MRI as performed for multislice CT. The 7 distal segments were classified as negative with MRI if no stenosis was seen in these segments. If a stenosis was seen in a distal segment with MRI, this segment was considered positive for MRI.
¶ One stenosis in a distal segment was correctly seen with MRI. Thus, the number of positive arteries on MRI in the analysis using all 15 coronary segments (68 arteries) was higher by 1 vessel than in the primary analysis (67 arteries).

Table 4. **Performance of Multislice Computed Tomography and Magnetic Resonance Imaging for Detecting Clinically Significant Coronary Stenoses and Identifying Patients with Coronary Artery Disease***

Variable	Multislice CT, *n/n (%)*	MRI, *n/n (%)*†	*P* Value†	MRI, *n/n (%)*‡	*P* Value‡
Analysis of patients					
Sensitivity §‖	56/61 (92 [82–96])	42/57 (74 [61–83])	0.013	42/61 (69 [56–79])	0.001
Specificity §‖	37/47 (79 [65–88])	38/51 (75 [61–84])	0.643	35/47 (74 [60–85])	0.815
Not interpretable ‖	8/108 (7 [4–14])	19/108 (18 [11–26])	0.052	19/108 (18 [12–26])	0.052
Negative predictive value	37/41 (90 [77–96])	38/45 (84 [71–92])	0.526	35/45 (78 [64–87])	0.150
Positive predictive value	56/59 (95 [86–98])	42/44 (95 [85–99])	1.000	42/44 (95 [85–99])	1.0
Analysis of coronary arteries					
Sensitivity §‖	110/134 (82 [75–89])	60/112 (54 [16–91])	<0.001	61/134 (46 [36–55])	<0.001
Specificity §‖	265/296 (90 [72–100])	278/318 (87 [47–100])	0.726	263/296 (89 [72–100])	0.864
Not interpretable ‖	28/430 (7 [3–10])	55/430 (13 [9–17])	0.017	55/430 (13 [9–17])	0.017
Negative predictive value	265/280 (95 [92–97])	278/308 (90 [70–100])	0.032	263/307 (86 [81–90])	<0.001
Positive predictive value	110/122 (90 [85–96])	60/67 (90 [79–100])	0.265	61/68 (90 [82–98])	0.269

* Values in brackets are 95% CIs. The CIs were estimated as described for unclustered data (patient level) (27, 28) and clustered data (vessel level) (29, 30). CT = computed tomography; MRI = magnetic resonance imaging.
† Using only the 8 proximal and middle coronary segments for MRI.
‡ Using all 15 coronary segments for MRI.
§ The differences in sensitivity in the per-patient and per-vessel analysis between multislice CT and MRI were 23 percentage points (CI, 11 to 35 percentage points) and 37 percentage points (CI, 26 to 47 percentage points), respectively. The differences in specificity in the per-patient and per-vessel analysis between multislice CT and MRI were 4 percentage points (CI, −13 to 22 percentage points) and 1 percentage point (CI, −13 to 14 percentage points), respectively. The CIs for these analyses were estimated for unclustered and clustered data on the patient (28) and vessel (31) level, respectively.
‖ "Not interpretable" results in the per-patient and per-vessel analyses were assumed to be false-negative or false-positive for the calculation of sensitivities and specificities, respectively, to avoid overestimation of diagnostic performance (22, 23).

CT and MRI were included in the comparison of diagnostic performance. Thus, 430 coronary arteries (left main, left anterior descending, left circumflex, and right) in 108 patients were analyzed. The median interval between the performance of the noninvasive tests and conventional coronary angiography was 1 day (mean, 0.7 day [range, 0 to 5 days]), and multislice CT and MRI were performed as same-day examinations in 78 patients (72%; mean interval, 0.1 day [range, 0 to 5 days]). The heart rates during multislice CT and MRI did not significantly differ (Table 1).

Diagnostic Performance

Figure 2 shows a representative coronary stenosis that was detected by using multislice CT and MRI. Tables 2 and 3 provide direct comparisons of multislice CT and MRI with conventional coronary angiography for the analysis of patients and coronary arteries, respectively. The MRI data are provided for the 8 proximal and middle vessel segments in the analysis and also for all 15 coronary segments. Table 4 summarizes the diagnostic performance of multislice CT and MRI per coronary artery and per patient. Again, the MRI data are provided both for the 8 proximal and middle vessel segments and all 15 coronary segments.

In the per-patient analysis, the sensitivity of multislice CT was significantly higher than that of MRI (92% vs. 74%; $P = 0.013$; Table 4), whereas the specificity was not significantly different (79% vs. 75%; $P = 0.643$). All 4 patients who had false-negative findings on multislice CT had single-vessel coronary disease with less than 60% diameter stenosis; 3 received medical treatment only. Of the 7 patients with false-negative MRI findings, 1 had 3-vessel disease, 2 had 2-vessel disease, and 4 had 1-vessel disease; revascularization was initiated in 4 patients. Further analyses of the per-patient diagnostic performance of multislice CT and MRI in patients with positive and negative findings on MRI and multislice CT, respectively (Appendix Table 1 and Appendix Table 2); for all 129 patients who completed the study (Appendix Table 3); and according to chest pain syndrome (Appendix Table 4 and Appendix Table 5) are available at www.annals.org.

In the per–coronary artery analysis, the sensitivities of multislice CT (for all 15 segments) and MRI (for the 8 proximal and middle segments) were 82% and 54%, respectively; the specificities were 90% and 87% ($P < 0.001$ and $P = 0.726$; Table 4).

When stenoses in all 15 coronary segments were analyzed for MRI, the sensitivity of MRI per coronary artery declined to 46% (61 of 134 coronary arteries; Table 4). Moreover, nonparametric analysis of repeated measurements, based on the 15-segment data for both tests, demonstrated significantly higher sensitivity for multislice CT than for MRI ($P < 0.001$), with significant differences among the 4 coronary arteries ($P = 0.003$).

Secondary Outcomes

Agreement between the 2 readers was achieved for 456 of the 502 coronary arteries examined by multislice CT (90.8%) and 400 of the 442 coronary arteries examined by MRI (90.5%). The Cohen κ in the per-vessel analysis was 0.82 (95% CI, 0.77 to 0.87) for multislice CT and 0.78 (CI, 0.72 to 0.84) for MRI, indicating close agreement between the observers. The Cohen κ in the per-patient analysis was 0.81 (CI, 0.72 to 0.90) for multislice CT and 0.80 (CI, 0.70 to 0.90) for MRI.

A total of 7 adverse events occurred in 6 of the 129 patients who completed the study. After conventional coronary angiography, 6 adverse events were experienced by 5 patients: 2 femoral false aneurysms and 4 cases in which a large groin hematoma occurred. All these complications were successfully treated without surgery, but they prolonged the in-hospital stay. One patient developed an allergic skin reaction 6 hours after intravenous administration of the contrast agent for multislice CT. This adverse event was probably related to the contrast agent; after appropriate medication the patient underwent conventional coronary angiography uneventfully.

The mean time spent by patients in the multislice CT suite was 17 minutes (SD, 6), as compared with 58 minutes (SD, 12) in the MRI and 58 minutes (SD, 17) in the angiography suite (excluding time necessary for interventions; *P* □ 0.001 for both comparisons with multislice CT). The effective radiation dose with multislice CT (12.3 mSv [SD, 1.4]) in a consecutive subgroup of 73 patients was not significantly different from that for cardiac catheterization (11.4 mSv [SD, 4.8]; *P* □ 0.169), whereas the amount of contrast agent administered for multislice CT (108.5 mL [SD, 10.7]) was significantly higher than that for conventional coronary angiography (94.8 mL [SD, 21.6]; *P* □ 0.001).

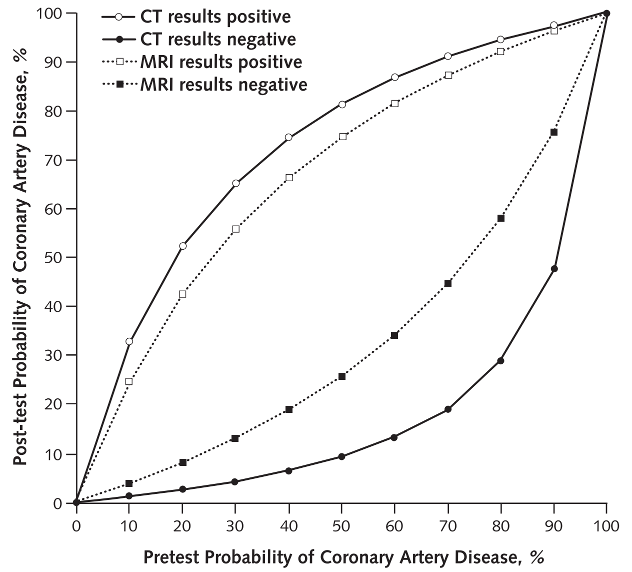
All 129 patients returned their questionnaires. Thirty-two patients (25%) indicated no pain during any procedure. Overall, the majority of patients felt the most pain during conventional angiography (67%), whereas 2% and 6%, respectively, felt the most pain during multislice CT and MRI. Most (74%) said they would prefer multislice CT to conventional coronary angiography and MRI for future diagnostic imaging of the coronary arteries (*P* □ 0.001).

DISCUSSION

In this study, the diagnostic performance of multislice CT was superior to that of MRI. Multislice CT offers the highest spatial resolution currently available for noninvasive coronary angiography. Preliminary studies in selected patients had previously shown an accuracy of about 80% to 95% for multislice CT with 12 and 16 detector rows (5–9). Our study not only confirms these results but also extends them to a larger consecutive series of patients with an intermediate prevalence and sinus rhythm. We also show in an intention-to-diagnose comparison the advantages of multislice CT over MRI. For clinical decision making, the results of the per-patient analysis for both noninvasive tests are most relevant. We have provided the per-patient predictive values of multislice CT and MRI for populations with different prevalences according to the Bayes theorem in Figure 3.

Recent technical advances have improved the diagnostic accuracy of noninvasive alternatives to conventional coronary angiography. Faster MRI techniques (24, 35) and the development of multislice CT scanners (36) have led to refined image quality and reassessment of the potential clinical applications of noninvasive coronary angiography. The unique feature of multislice CT is that multiple x-ray detector rows (in this case, 16) are simultaneously used to acquire source data with a fast gantry rotation time. Thus, thin slice widths (in this case, 0.5 mm) can be combined with large organ coverage and high temporal resolution. The imaging time of multislice CT, and therefore also the breath-hold time and amount of contrast agent needed, will be further reduced with scanners using 64 detector rows, which have recently become available (37). A study comparing 16- and 64-slice CT for coronary angiography in a single patient cohort is highly desirable but has not been performed. The diagnostic accuracy reported for coronary MRI has varied greatly among the published single-center studies (24). The spatial resolution of MRI remains an important limiting factor that makes detection of coronary stenoses in distal segments problematic. In a multicenter study that excluded patients with contraindications to MRI and analyzed 7 proximal and middle coronary segments, an overall per-vessel accuracy of 65% was achieved when nondiagnostic coronary arteries were included in the analysis (11). We achieved higher diagnostic

Figure 3. **Per-patient post-test probabilities after multislice computed tomography (*CT*) and magnetic resonance imaging (*MRI*) for hypothetical populations with different prevalences of disease according to the Bayes theorem based on sensitivities and specificities in Table 4.**



To identify first implications of the results for clinical decision making (according to Bayesian interpretation), we calculated the post-test probability after positive and negative findings on multislice CT and MRI for populations with different pretest probabilities of coronary artery disease.

accuracy even when all 15 coronary segments were included. Computed tomography and MRI technology are evolving rapidly (10, 37–41), and our study provides a snapshot in time. However, the new technology may not necessarily lead to measurable differences in test performance, at least in the short term.

The total room time required for imaging was lowest for multislice CT, and study participants indicated a strong preference for multislice CT over conventional coronary angiography and MRI. Multislice CT could not be used to evaluate 7% of the coronary arteries and 7% of patients. However, MRI showed worse results, with findings from 13% of the vessels and 18% of the patients being uninterpretable. This high rate hinders the routine application of MRI.

Our study has some limitations. In the present study, preoxygenation was used for multislice CT only, but it might also improve the results of breath-hold MRI as shown for volunteers (42). T2 preparation for coronary MRI has been shown to improve the contrast and visibility of smaller branches of the coronary arteries in healthy volunteers (43) but was not used in our study. Only stenoses with a reference vessel diameter of at least 1.5 mm (targets for revascularization) were included in our comparison. A regular heartbeat is a prerequisite for noninvasive coronary imaging, which limits the application of both tests, and we did not record the number of patients without sinus rhythm or other contraindications who were ineligible. The study is also limited by its single-center design and inclusion of a small number of patients. Larger multicenter studies will need to examine multislice CT for the diagnosis of coronary stenoses. Future studies also appear essential for evaluating the prognostic importance of multislice CT for detection of coronary artery plaques and evaluation of cardiac function. The ionizing radiation of CT is a drawback of this noninvasive test (44) that limits its application for serial measurements (for example, during stress and at rest) and follow-up examinations (such as for plaque assessment). In the present study, the effective radiation dose with 16-slice CT did not differ from that for conventional coronary angiography. With 64-slice CT, however, higher doses are expected because of increased scattered radiation. Of course, patients who undergo noninvasive imaging and are found to have a clinically significant stenosis may require subsequent conventional angiography, since there is no prospect of an interventional capability with noninvasive techniques.

In summary, multislice CT is superior to MRI for the detection of coronary artery stenoses, and the high negative predictive value of multislice CT for the presence of coronary stenoses (95%) makes it potentially useful as a diagnostic tool for ruling out coronary disease in a population with a low to intermediate pretest likelihood. These findings suggest that multislice CT of the coronary arteries can be used successfully as a diagnostic test in some patients before conventional coronary angiography.

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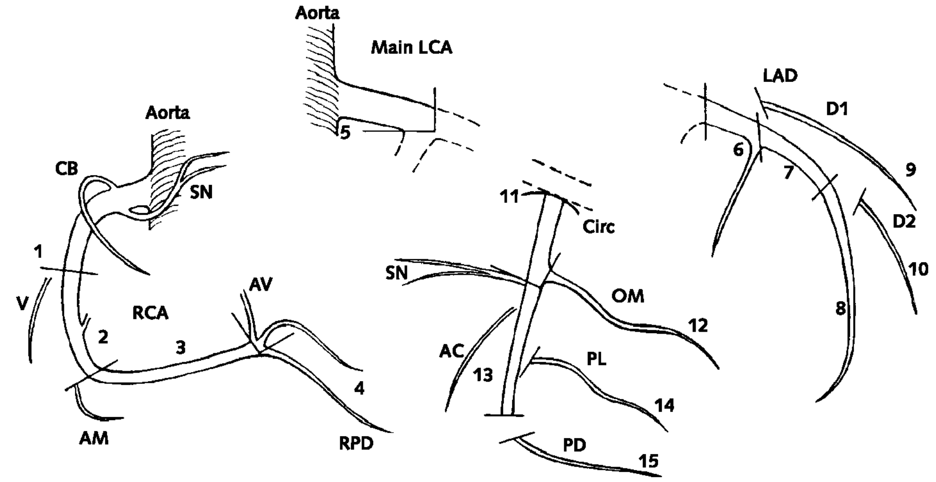
along the coronary arteries (17). Stenoses were quantified on images orthogonal to the vessel (cross-sectional images) as described elsewhere (17).

MRI Protocol

Before MRI, the patients were extensively trained to breathe regularly and quietly and not to fall asleep during the free-breathing study, in order to increase the efficiency of the right diaphragmatic navigator gating used (47). A noncontrast, magnetization-prepared 3-dimensional balanced steady-state free precession sequence (true fast imaging with steady-state precession) (18, 48) was acquired during free breathing (acquired slice width, 2.4 mm; interpolated slice width, 1.2 mm; pixel size, 0.9 × 0.7 mm, equal to a voxel volume of 1.5 mm^3) and end-expiratory breath-hold (acquired slice width, 3.0 mm; interpolated slice width, 1.5 mm; pixel size, 1.5 × 0.7 mm, equal to a voxel volume of 3.1 mm^3), with the following parameters: echo time, 1.8 and 1.6 milliseconds; repetition time, 4.3 and 3.7 milliseconds; field of view, 360 × 247 and 380 × 166 mm; matrix size, 512 × 282 and 512 × 112 pixels; number of slices, 30 to 40 and 10 to 16; flip angle, 65 degrees and 65 degrees; bandwidth, 510 and 610 Hz/pixel; and total imaging time, 153 to 198 and 20 to 32 heartbeats, respectively (18). For contrast enhancement between blood and the surrounding epicardial fat, a frequency-selective fat-saturation prepulse was applied. Asymmetric sampling of echoes was operated to reduce imaging time and off-resonance artifacts (35). The R wave of the electrocardiogram, simultaneously recorded via an active system, was used as the trigger for image acquisition, and a patient-based trigger delay and acquisition interval per heartbeat (and thus also a patient-specific number of excitations per heartbeat) were applied to start the acquisition during the phase with the least motion of the right and left coronary artery, respectively (49). The average trigger delays after the R wave for the right and left coronary artery were 407 and 452 milliseconds, respectively, while the average lengths of the image acquisition interval were 98 and 104 milliseconds. To improve vessel sharpness and contrast-to-noise ratio in free-breathing MRI, prospective real-time adaptive motion correction with a right diaphragmatic localizer navigator gating window of 5 mm and a tracking factor of 0.6 was used. The free-breathing study lasted 6.4 minutes (SD, 1.7) for acquisition of one 3-dimensional data stack. Using free-breathing acquisition as the only approach in a study that represents all sorts of patients during clinical practice (including older and less adherent patients) is not sufficient because unselected patients have much less reliable free-breathing patterns than do healthy volunteers or selected patients (50). One study compared both breathing approaches and found no significant differences in diagnostic accuracy (51); thus, depending on each patient's abilities, free-breathing or breath-hold acquisitions might be used for analysis in the sense of a combined approach (18). Only when irregular breathing patterns resulted in increased image blurring that prevented adequate diagnostic assessment in a free-breathing study were the breath-hold images acquired for analysis (40% of acquisitions). The true consecutive inclusion of all patients meeting the inclusion criteria during the study period, regardless of their mental fitness and ability to breathe regularly, may explain the lower success rate of free-breathing coronary MRI in our study compared with previous studies (11, 52). Thus, a combined approach of free-breathing and high-resolution breath-hold acquisitions is a viable alternative in patients with suspected coronary artery disease (18). Magnetic resonance images were analyzed by using a magnetic resonance angiography protocol of the workstation (Vitrea 2, version 3.3). Three-dimensional evaluation of the MRI data sets was performed by using volume rendering (normal or direct light) with a "hard ramp" transparency, the "tissue-tone" or "heat scale" coloring, and a telephoto (15 degrees) or moderate-angle (45 degrees) view option.

Appendix Figure. **American Heart Association classification of coronary artery segmental anatomy.**



Coronary artery segments are numbered 1 through 15. Minor branches, such as the conus (*CB*), sinus node (*SN*), ventricular (*V*), acute marginal (*AM*), atrioventricular node (*AV*), and atrial circumflex (*AC*) branches, are indicated in the diagram only for general orientation. These branches may or may not be visualized in the individual patient. Those whose origins can vary widely are shown unattached to the parent artery. Circ = left circumflex coronary artery; D1 = first diagonal branch; D2 = second diagonal branch; LAD = left anterior descending coronary artery; main LCA = left main coronary artery; OM = obtuse marginal branch; PD = posterior descending branch; PL = posterolateral branch; RCA = right coronary artery; RPD = right posterior descending branch. Adapted from Austen et al. (19).

Appendix Table 1. **Performance of Multislice Computed Tomography for the Detection of Coronary Artery Disease in Patients with Positive and Negative Results on Magnetic Resonance Imaging***

Test Characteristic of Multislice CT	Positive Result on MRI (*n* = 44), *n/n (%)*†	Negative Result on MRI (*n* = 45), *n/n (%)*†
Sensitivity	41/42 (98 [87–100])	6/10 (60 [26–88])
Specificity	0/2 (0 [0–84])	27/35 (77 [60–90])

* Data in brackets are 95% CIs. The CIs were estimated for unclustered data. CT = computed tomography; MRI = magnetic resonance imaging.
† Using only the 8 proximal and middle coronary segments for MRI. The numbers of positive (*n* = 44) and negative (*n* = 45) MRI results are derived from the predictive values of MRI (Table 4) and do not add up to the number of CTs (*n* = 100) in Appendix Table 2 because of a higher number of MRI scans that could not be interpreted.

Appendix Table 2. **Performance of Magnetic Resonance Imaging for the Detection of Coronary Artery Disease in Patients with Positive and Negative Results on Multislice Computed Tomography***

Test Characteristic of MRI	Positive Result on Multislice CT (*n* = 59), *n/n (%)*†	Negative Result on Multislice CT (*n* = 41), *n/n (%)*†
Sensitivity	41/53 (77 [64–88])	1/4 (25 [1–81])
Specificity	4/6 (67 [22–96])	27/37 (73 [56–86])

* Data in brackets are 95% CIs. The CIs were estimated for unclustered data. CT = computed tomography; MRI = magnetic resonance imaging.
† Using only the 8 proximal and middle coronary segments for MRI. The numbers of positive and negative CT results are derived from the predictive values of CT presented in Table 4.

Appendix Table 3. **Performance of Multislice Computed Tomography and Magnetic Resonance Imaging in All 129 Patients Who Completed the Study***

Variable	Multislice CT, *n/n (%)*	MRI, *n/n (%)*†	*P* Value†	MRI, *n/n (%)*‡	*P* Value‡
Analysis of patients					
Sensitivity	62/67 (93 [83–98])	42/63 (67 [54–78])	<0.001	42/67 (63 [50–74])	<0.001
Specificity	46/62 (74 [62–84])	39/66 (59 [46–71])	0.092	36/62 (58 [45–70])	0.087
Not interpretable§	12/129 (9 [5–16])	39/129 (30 [22–39])	<0.001	39/129 (30 [22–39])	<0.001
Negative predictive value	46/50 (92 [81–98])	39/46 (85 [71–94])	0.343	36/46 (78 [64–89])	0.082
Positive predictive value	62/67 (93 [83–98])	42/44 (95 [85–99])	0.701	42/44 (95 [85–99])	0.701
Analysis of coronary arteries					
Sensitivity	118/142 (83 [77–90])	60/119 (50 [13–87])	<0.001	61/142 (43 [34–52])	<0.001
Specificity	321/372 (86 [72–100])	283/395 (72 [34–100])	0.001	268/372 (72 [61–83])	0.001
Not interpretable§	44/514 (9 [5–12])	134/514 (26 [20–33])	<0.001	134/514 (26 [20–33])	<0.001
Negative predictive value	321/336 (96 [93–99])	283/313 (90 [70–100])	0.007	268/312 (86 [81–90])	<0.001
Positive predictive value	118/134 (88 [82–94])	60/67 (90 [79–100])	0.443	61/68 (90 [82–98])	0.448

* Values in brackets are 95% CIs. The CIs were estimated for both analyses as described for sensitivities and specificities (30) and accuracy, rates, and predictive values (29). CT = computed tomography; MRI = magnetic resonance imaging.
† Using only the 8 proximal and middle coronary segments for MRI.
‡ Using all 15 coronary segments for MRI.
§ "Not interpretable" results included patients and arteries that could not be examined or were uninterpretable.

Appendix Table 4. **Performance of Multislice Computed Tomography and Magnetic Resonance Imaging for the Detection of Coronary Artery Disease in the 61 Patients with Typical Angina Pectoris***

Test Characteristic	Multislice CT	MRI†	*P* Value†
Sensitivity	43/47 (91 [80–98])	27/44 (61 [46–76])	<0.001
Specificity	10/14 (71 [42–92])	11/17 (65 [38–86])	0.99

* Values in brackets are 95% CIs. The CIs were estimated for unclustered data. CT = computed tomography; MRI = magnetic resonance imaging.
† Using only the 8 proximal and middle coronary segments for MRI. *P* values were obtained by using nonparametric analysis for repeated measurements (26).

Appendix Table 5. **Performance of Multislice Computed Tomography and Magnetic Resonance Imaging for the Detection of Coronary Artery Disease in the 32 Patients with Atypical Angina Pectoris***

Test Characteristic	Multislice CT	MRI†	*P* Value†
Sensitivity	11/12 (92 [62–100])	8/11 (73 [39–94])	0.82
Specificity	14/20 (70 [46–88])	13/21 (62 [38–82])	0.68

* Values in brackets are 95% CIs. The CIs were estimated for unclustered data. CT = computed tomography; MRI = magnetic resonance imaging.
† Using only the 8 proximal and middle coronary segments for MRI. *P* values were obtained by using nonparametric analysis for repeated measurements (26). In this exploratory analysis of patients with atypical symptoms, the diagnostic accuracy for patients with atypical angina does not appear to be lower than for patients with typical angina (Appendix Table 4).