AHA Scientific Statement

Noninvasive Coronary Artery Imaging

Magnetic Resonance Angiography and Multidetector Computed Tomography Angiography

A Scientific Statement From the American Heart Association Committee on Cardiovascular Imaging and Intervention of the Council on Cardiovascular Radiology and Intervention, and the Councils on Clinical Cardiology and Cardiovascular Disease in the Young

David A. Bluemke, MD, PhD, FAHA, Chair; Stephan Achenbach, MD; Matthew Budoff, MD, FAHA; Thomas C. Gerber, MD, FAHA; Bernard Gersh, DPhil, MD, FAHA; L. David Hillis, MD; W. Gregory Hundley, MD, FAHA; Warren J. Manning, MD, FAHA; Beth Feller Printz, MD, PhD; Matthias Stuber, PhD; Pamela K. Woodard, MD, FAHA

Since the early 1960s, selective x-ray coronary angiography has provided the only means of visualizing the coronary arterial system in vivo. However, it has several disadvantages. First, the incidence, albeit relatively low, of so-called major adverse events (death, myocardial infarction, or stroke) during or within 24 hours of selective coronary angiography is reported to be 0.2% to 0.3%, and the incidence of so-called minor complications (most of which are related to problems with the peripheral vessels through which catheters are inserted) is roughly 1% to 2%.[1–3] Second, x-ray coronary angiography is accompanied by a modest amount of discomfort, because the placement of catheters is invasive. Third, it is expensive: the required equipment is costly, and the performance of the procedure necessitates considerable time and skill of highly trained physicians and support personnel. Last, the information obtained via catheter-based coronary angiography pertains to the coronary arterial lumen alone. As a result, alternative methods of visualizing the coronary arterial system that would allow one to avoid these disadvantages are desirable.

Over the past 15 years, substantial advances have been made in noninvasive cardiac imaging in general and in visualization of the coronary arteries in particular. Magnetic resonance angiography (MRA) of the coronary arteries was advanced in the early 1990s with the development of high-speed gradient techniques and dedicated cardiac coils. The primary advantage of this technique is the patient's lack of exposure to ionizing radiation or iodinated contrast media. Coronary MRA may also be combined with other magnetic resonance (MR) imaging techniques for assessment of cardiac function, structure, blood flow, and viability.[4]

Electron-beam computed tomography (CT) with iodinated contrast injection was originally used to perform coronary angiograms, but this has been supplanted by multidetector CT (MDCT) scanners that have 16 to 256 rows of detectors. MDCT can provide visually compelling images of the coronary arterial tree, although at present, the necessary radiation dose is higher than that associated with x-ray coronary angiography.

In this statement, we discuss and summarize these two noninvasive modalities, MRA and computed tomographic angiography (CTA), which may be used for coronary artery evaluation. Because the advantages and limitations of CT to assess the presence and extent of coronary arterial calcification are discussed in a separate document sponsored by the American Heart Association, the assessment of coronary arterial calcification is not presented in this statement. For both MRA and CTA, we provide a discussion of technical issues, applications, advantages, and

This statement was approved by the American Heart Association Science Advisory and Coordinating Committee on April 2, 2008. A single reprint is available by calling 800-242-8721 (US only) or by writing the American Heart Association, Public Information, 7272 Greenville Ave, Dallas, TX 75231-4596. Ask for reprint No. 71-0452. A copy of the statement is also available at http://www.americanheart.org/presenter.jhtml?identifier=3003999 by selecting either the "topic list" link or the "chronological list" link. To purchase additional reprints, call 843-216-2533 or e-mail kelle.ramsay@wolterskluwer.com.

Expert peer review of AHA Scientific Statements is conducted at the AHA National Center. For more on AHA statements and guidelines development, visit http://www.americanheart.org/presenter.jhtml?identifier=3023366.

(*Circulation*. 2008;118:000-000.)

Circulation is available at http://circ.ahajournals.org DOI: 10.1161/CIRCULATIONAHA.108.189695

limitations, after which we offer recommendations for current and future uses. To accomplish this, the Writing Committee conducted a comprehensive review of the literature published between 1990 and 2006. Literature searches of the PubMed/MEDLINE databases were undertaken to identify pertinent articles. Searches were limited to the English language. The major search terms included the following: *coronary angiography*, *coronary disease*, *coronary vessels*, *humans*, *magnetic resonance angiography*, *tomography*, and *x-ray computed*.

MRA of the Coronary Arteries

Technical Considerations for Coronary MRA

Images of the heart must be obtained rapidly and with high temporal resolution to reduce motion artifacts that could otherwise cause blurring in coronary MRA images. Unlike angiographic images obtained via catheter, MRA (and CTA) images take a long time to acquire; for example, high-resolution MRA visualization of the entire coronary arterial tree takes minutes rather than seconds. In addition, cardiac motion must be accounted for during this time period.

Cardiac Motion

Two sources of motion are associated with coronary MRA: motion related to intrinsic cardiac contraction/relaxation and motion attributable to superimposed diaphragm and chest wall movement during respiration. Because the extent of motion exceeds the diameter of the coronary artery, blurring artifacts of the coronary artery lumen will occur unless adequate motion-suppression techniques are applied. ECG gating is used to account for intrinsic cardiac motion.

Coronary artery motion occurs in a triphasic pattern during the cardiac cycle. Mid-diastole is the preferred time for image acquisition, because cardiac motion is minimized while coronary flow is high. The patient-specific diastasis period (of reduced coronary motion) is usually determined by visual inspection of cine images perpendicular to the long axis of the proximal/mid-right coronary artery (RCA). Multiple heartbeats are required to generate a coronary MRA. The beat-to-beat variation in the duration of the cardiac cycle and the period of diastasis results in image blurring. β-Blockade prolongs the period of coronary diastasis and may help to improve the quality of coronary MRA images.

Respiratory Motion

A straightforward approach to suppressing respiratory motion involves the use of breath-holding during coronary MRA. However, breath-holding strategies have several limitations. First, spatial and temporal image resolution is limited by the patient's ability to hold his or her breath. Some patients may have difficulty sustaining adequate breath-holds, particularly when the procedure lasts longer than a few seconds. Additionally, it has been shown that during a sustained breath-hold, there is up to 1 cm of cranial diaphragmatic (and thus cardiac) drift.[5–7] Thus, at present, breath-hold strategies for coronary MRA have limited applicability to the broad range of patients with cardiovascular disease.

To overcome these limitations, so-called navigator echoes[8–11] (similar to M-mode echocardiographic beams) can be used during free-breathing coronary MRA to track a patient's diaphragmatic motion. MRA images are acquired only when the diaphragm is within 3 to 5 mm of its end-expiratory position. Respiratory blurring is minimized with this method and may be further reduced by using real-time tracking of the imaged volume position.[9]

Free-breathing navigator coronary MRA offers improved patient comfort as compared with breath-holding techniques and does not require significant patient motivation. However, this method prolongs the duration of the coronary MRA, because image data are collected only when the end-expiratory position of the diaphragm coincides with the period of coronary artery diastasis.[12] Typical examination times for free-breathing 3D navigator coronary MRA are 7 to 15 minutes.

Spatial Resolution

The spatial resolution achievable with 3D MRA imaging (0.7 to 0.8 mm in-plane resolution and 1 to 3 mm through-plane resolution) is inferior to that obtainable with x-ray coronary angiography ($<$0.3 mm).

For MRA imaging, improvement in spatial resolution is generally accompanied by reduction in the signal-to-noise ratio (SNR). As the voxel size is reduced toward the resolution achievable with x-ray angiography, methods to reduce motion artifacts from both intrinsic and extrinsic motion of the coronary arteries become increasingly important.[13]

Contrast Enhancement in Coronary MRA

Coronary MRA examinations are typically performed without the addition of intravenously administered contrast agents. The relative signal of the coronary arteries is augmented using fat-saturation prepulses,[14] magnetization transfer contrast prepulses,[15] or T2 preparatory pulses,[16,17] which take advantage of natural T2 differences between the blood and the surrounding myocardium. When these techniques are used, the coronary lumen appears bright, whereas the surrounding myocardium has reduced signal intensity. The lack of exposure to ionizing radiation and the absence of exogenous contrast agents facilitate repeat MRA studies when clinically warranted.

With the use of intravenous MR contrast agents, the T1 relaxation time for blood can be shortened, which allows for an increased contrast-to-noise ratio for coronary MRA.[18,19] The extravascular contrast agents that are presently available in the United States for coronary MRA quickly extravasate from the coronary lumen. Use of these agents requires rapid first-pass imaging, which necessitates breath-holding[20] and results in images with reduced spatial resolution (as discussed in Spatial Resolution, above).

Recent Technical Developments

Technical improvements in coronary MRA include the development of MR methods that generate improved coronary signals and support reduced scanning times while simultaneously minimizing the complexity of the examination.

Steady-State With Free-Precession Coronary MRA

Use of the steady-state with free-precession (SSFP) method to perform MRA makes it possible to obtain high signal intensity from the coronary arteries and very high contrast between the ventricular blood pool and the myocardium without the need for contrast agents.[21] SSFP imaging permits high-quality coronary MRA during free-breathing with substantial improvements in SNR, contrast-to-noise ratio, and vessel sharpness as compared with standard T2-prepared gradient-echo imaging.[22] Therefore, SSFP imaging may lead to improved identification of significant coronary artery stenoses. At present, SSFP is being evaluated at many clinical and research centers.

Phase-Contrast MR Imaging

The phase-contrast technique measures blood-flow velocity[23] combined with arterial diameter to yield a quantitative measurement of blood flow (in milliliters per minute). Blood flow can be determined when a patient is at rest or after he or she is stressed for measurement of coronary artery blood-flow reserve.[23,24] Although it has been demonstrated in clinical research, this method can be applied on most 1.5-Tesla and some 3.0-Tesla MR scanners. Coronary blood flow is measured along a 2-cm straight proximal or mid-arterial segment in vessels that are >2 mm in diameter.[25]

Parallel Imaging for Coronary MRA

Parallel imaging is an MR method for reducing MR scanning time by a factor of 2 to 3.[26] However, the trade-off for reduced acquisition time is reduced SNR for visualization of the coronary arteries.

3-Tesla Coronary MRA

Most coronary MRA examinations are performed on 1.5-Tesla MR systems. Higher field, 3-Tesla systems provide better signal and contrast values relative to 1.5-Tesla systems. The recent availability of 3-Tesla systems equipped with dedicated cardiac hardware (eg, real-time spectrometer, parallel receiver technology with high bandwidth, body radiofrequency send coil, vector ECG) and software (parallel imaging, navigators, interactive interface) may provide a means for substantial coronary MRA improvements in the future.[27]

Whole-Heart Coronary MRA

Until recently, coronary MRA was performed with only portions of each arterial tree visible in each set of images.[28] This method requires the MR imaging technologist to have extensive experience and familiarity with coronary artery anatomy. The recent development of whole-heart coronary MRA, which is analogous to coronary CTA, allows for imaging of the entire coronary artery tree in an axially acquired 3D volume. Postprocessing of the 3D images is performed in a manner similar to that for coronary CTA. To collect such large volumetric data sets, spatial resolution is somewhat lower (usually >1 mm in-plane and through-plane resolution), data are collected over approximately 100 ms of each cardiac cycle (with potential for blurring), and scan times are lengthy (10 to 15 minutes), thereby mandating the use of navigator echoes. Nevertheless, the whole-heart coronary MRA approach has gained rapid acceptance on the basis of promising initial results.[29]

Table 1. Coronary MRA for Anomalous Coronary Artery Evaluation

Reference	No. of Patients	Correctly Classified Anomalous Vessels, n (%)
McConnell et al[30]	15	14 (93)
Post et al[32]	19	19 (100)*
Vliegen et al[33]	12	11 (92)†
Taylor et al[31]	25	24 (96)
Bunce et al[37]	26	26 (100)‡
Razmi et al[36]	12	12 (100)

*Numbers include 3 patients originally misclassified with x-ray angiography.

†Numbers include 5 patients who could not be classified with x-ray angiography.

‡Numbers include 11 patients who could not be classified with x-ray angiography.

Clinical Applications and Results

Anomalous Coronary Artery

Projection x-ray angiography has traditionally been the imaging test of choice for the diagnosis and characterization of coronary artery anomalies. However, the presence of an anomalous coronary artery origin is sometimes only suspected after the invasive procedure, particularly in the case of unsuccessful engagement or visualization of a coronary artery. In addition, the declining use of pulmonary artery catheters during routine x-ray coronary angiography has made it more difficult to discern the anterior versus the posterior trajectory of the anomalous vessels.

Multiple published series exist[30–33] of patients who underwent blinded comparison of coronary MRA with x-ray angiography (Table 1). Early coronary MRA studies often used a 2D breath-hold ECG-triggered segmented k-space gradient-echo approach.[30–36] These 2D coronary MRA studies uniformly reported excellent accuracy, including several studies in which coronary MRA was determined to be superior to x-ray angiography.[31,32] At most centers, 3D coronary MRA is now used, because it offers superior reconstruction capabilities with similarly excellent results.[37] For these reasons, coronary MRA is the preferred test for younger patients in whom an anomalous artery origin is suspected or a known anomalous coronary artery origin needs to be clarified and for patients who have another cardiac anomaly associated with coronary anomalies (eg, tetralogy of Fallot).

Coronary Artery Aneurysms/Kawasaki Disease

Although coronary artery aneurysms are relatively uncommon, recent studies indicate an important role for coronary MRA for assessment of this condition. The vast majority of acquired coronary aneurysms in children and younger adults are due to Kawasaki disease, a generalized vasculitis of unknown etiology that usually occurs in children under 5 years old. Approximately 5% of patients develop coronary

Table 2. MRA for the Detection of Coronary Artery Stenosis

Reference	Technique	No. of Patients	Sensitivity, %*	Specificity, %*	Negative Predictive Value, %*	Remarks
Manning et al[206]	2D BH	39	90	92	88	Per-artery analysis, proximal and mid segments
Pennell et al[207]	2D BH	39	85	...	...	Per-artery analysis
Post et al[208]	2D BH	35	63	89	81	Per-artery analysis, proximal and mid segments
Woodard et al[209]	3D Nav, retro	10	70	...	...	Per-artery analysis, proximal and mid segments
Kessler et al[210]	3D Nav, retro	73	65	88	92	Per-patient analysis, 52% evaluable segments
Sandstede et al[211]	3D Nav, retro	30	81	89	...	Per-patient analysis, all segments
van Geuns et al[212]	3D Nav, retro	20	73	50	90	Per-segment analysis, proximal and mid segments
Huber et al[213]	3D Nav, retro	32	50	91	...	Per-artery analysis, proximal and mid segments
Sardanelli et al[214]	3D Nav, retro	42	82	89	93	Per-segment analysis, all segments
Wittlinger et al[215]	3D Nav, retro	20	75	100	...	Per-segment analysis, proximal and mid segments
Kim et al[216]†	3D Nav, pros	109	93	42	81	Per-artery analysis, proximal and mid segments
Weber et al[217]	3D Nav, pros	15	88	94	96	Per-patient analysis; all segments for LAD, 70% segments evaluable for RCA
Sakuma et al[29]	3D Nav, pros	39	82	91	93	Per-segment analysis, all segments
Dewey et al[45]	3D Nav, pros	30	65	74	71	Per-segment analysis, all segments
Jahnke et al[218]	3D Nav, pros	55	78	91	...	Per-segment analysis, all segments
Regenfus et al[219]	3D BH	50	94	57	80	Per-patient analysis, proximal and mid segments, 77% evaluable segments
van Geuns et al[56]	3D BH	38	68	97	94	Per-patient analysis, distal segments for RCA only, 69% evaluable segments

2D BH indicates 2-dimensional breath-hold; 3D Nav, retro, 3-dimensional navigator, retrospective gating; 3D Nav, pros, 3-dimensional navigator, prospective gating; 3D BH, three-dimensional breath-hold; and LAD, left anterior descending artery.

*Sensitivity, specificity, and negative predictive value based on luminal stenosis >50%.

†Multicenter trial.

artery ectasia or aneurysms despite appropriate therapy.[38–40] Good correlation between coronary MRA and x-ray coronary angiography has also been reported for ectatic coronary arteries (distinct from Kawasaki disease) among adults.[41]

Coronary MRA for Identification of Native Vessel Coronary Stenoses

The results of coronary MRA in single-center trials are presented in Table 2. No efficacy data have been reported regarding "screening" coronary MRA in high-risk populations.

A multicenter single-vendor study of 3D coronary MRA in 109 patients demonstrated 93% sensitivity, 58% specificity, and 81% negative predictive value for the identification of ≧50% diameter stenosis by quantitative coronary angiography (Table 3).[28] The sensitivity and negative predictive value were particularly high for the identification of left-main or multivessel disease, thereby demonstrating a role for coronary MRA for this subset. Accordingly, coronary MRA may be valuable for rendering a diagnosis for patients who present with dilated cardiomyopathy/congestive heart failure in the absence of clinical infarction and for determining whether the problem is ischemic or nonischemic. A limitation of this study for general application of the results was the use of MR scanners from the same vendor at all sites.

Single-center data obtained from using free-breathing navigator-gated whole-heart MRA suggest that the whole-heart approach provides faster acquisitions (<15 minutes) and superior accuracy,[29,42–46] with sensitivities of 80% to 90% and specificity of >90%. Two comparison studies of coronary MRA and 16-slice MDCT demonstrated similar accuracy when compared with free-breathing coronary MRA[47] and superior results for MDCT when compared with a combination of free-breathing and lower-resolution breath-hold coronary MRA.[48]

At experienced research centers, phase-contrast MR coronary artery flow measurements can provide supplemental information regarding the physiological importance of coro-

Table 3. Three-Dimensional Navigator Coronary MRI: Multicenter Trial Results

	Per-Patient Analysis, %	Left Main/3-Vessel Disease, %
Sensitivity	93	100
Specificity	42	85
Prevalence	59	15
Positive predictive value	70	54
Negative predictive value	81	100

Adapted from Kim et al.[216]

nary artery luminal narrowing.[49–54] Impaired coronary flow reserve measured by MR identifies coronary arterial luminal stenosis of >70% in the left-main and proximal coronary artery segments when the angiographic appearance of the stenosis is of intermediate severity.[49–51] In individuals who have undergone percutaneous coronary artery stent placement in the left anterior descending coronary artery, impaired phase-contrast MR flow-reserve measurements reliably identify luminal renarrowing of >50% for symptomatic patients 3 months or more after stent implantation.[52,55]

The results discussed above were obtained at research-oriented centers that have the capability to perform high-quality MRCA in either single-center or single-vendor trials. The utility of coronary MRA in general practice has not been established, and multivendor trials have not been conducted.

Coronary MRA for Coronary Artery Bypass Graft Assessment

Conventional free-breathing ECG-gated 2D spin-echo MRA[56–59] and 2D gradient-echo MRA[60–63] in the transverse plane have both been used with knowledge of the origin and touchdown site of each graft to reliably assess bypass graft patency (Table 4). Additionally, both 3D noncontrast[64] and contrast-enhanced coronary MRA have been used for assessment of graft patency,[65,66] with slightly improved results. The accuracy of ECG-gated SSFP sequences appears to be similar to that of spin-echo and gradient-echo approaches.[67]

A practical limitation of coronary MRA bypass graft assessment is related to local signal loss and artifacts that are caused by nearby metallic objects (hemostatic clips, ostial stainless steel graft markers, sternal wires, coexistent prosthetic valves and supporting struts or rings, and graft stents). Although coronary MRA has been successfully used for identification of graft occlusion, the inability to identify various degrees of luminal narrowing in diseased yet patent grafts is also a hindrance to clinical utility and acceptance.

CTA of the Coronary Arteries

CTA Techniques and Technical Issues

Because of the high motion velocity of the coronary arteries, CT scanners must have sufficiently high temporal resolution to provide images of the beating heart with minimal motion artifact. Depending on the patient's heart rate during the scan and the phase of the cardiac cycle at which the coronary arteries are captured, a temporal resolution of 19 to 75 ms is desirable for coronary CTA.[68,69] Similar to coronary MRA, coronary CTA temporal resolution is currently lower than is optimal for coronary artery depiction.

Multidetector Computed Tomography

MDCT scanners (also known as multislice CT) with x-ray tubes rotating fast enough to allow coronary artery imaging (500 ms or less per rotation) became available in the late 1990s.[70,71] The temporal resolution of MDCT is approximately half the time it takes for the x-ray gantry to complete a 360° rotation around the patient when a half-segment reconstruction is used. The nominal temporal resolution can be improved by a factor of 2 to 3 (depending on the heart rate) by segmented reconstruction techniques that combine proj-

Table 4. Evaluation of Coronary Artery Bypass Graft Patency by Coronary MRA

Reference	Technique	No. of Grafts	Patency, %	Sensitivity, %*	Specificity, %*	Accuracy, %
White et al[59]	2D spin-echo	72	69	86	59	78
Rubenstein et al[220]	2D spin-echo	47	62	90	72	83
Jenkins et al[221]	2D spin-echo	41	63	89	73	83
Galjee et al[61]	2D spin-echo	98	74	98	85	89
White et al[60]	2D GRE	28	50	93	86	89
Aurigemma et al[62]	2D GRE	45	73	88	100	91
Galjee et al[61]	2D GRE	98	74	98	88	96
Engelmann et al[63]	2D GRE	17 IMA	100	100	...	100
		38 SVG	66	92	85	89
Molinari et al[64]	3D GRE	51	76.5	91	97	96
Bunce et al[67]	3D SSFP	23 IMA	96	73	100	74
		56 SVG	82	89	40	80
Wintersperger et al[66]	3D gad MRA	28 IMA	89	96	67	...
		48 SVG	73	94	85	...
Vrachliotis et al[65]	3D gad MRA	44	68	93	97	95

GRE indicates gradient-recalled echo; IMA, internal mammary artery graft; SVG, saphenous vein graft; and gad MRA, gadolinium MRA.
*Sensitivity and specificity based on luminal stenosis >50%.

ection data acquired during 2 or more cardiac cycles into 1 image.[70,72] Currently, MDCT scanners can acquire up to 64 slices simultaneously with a maximum temporal resolution as low as 83 ms (dual-source MDCT).[73]

In MDCT coronary CTA, image data are acquired throughout the cardiac cycle while the patient table continuously advances through the gantry. Electrocardiographic information is used to retrospectively reconstruct images from projection data acquired during the phase of the cardiac cycle with the least cardiac motion. The speed of the patient table relative to the speed of the gantry rotation (called pitch) is such that each cross-sectional level of the heart is imaged during more than 1 cardiac cycle. The number of image slices acquired during each gantry rotation (currently ranging from 16 to 320) determines the overall duration of the MDCT scan but does not directly influence the temporal resolution.

Spatial Resolution

The smallest x-ray beam collimation possible with a given CT scanner dictates the minimal thickness of the image slices that can be reconstructed. The slice thickness affects spatial resolution. High spatial resolution allows assessment of small side branches of the coronary arteries, decreases artifacts due to partial-volume effects, and leads to better assessment of calcified coronary artery segments and in-stent stenoses. However, to have sufficiently low image noise with smaller x-ray beam collimation, a large increase of the x-ray dose is necessary.

Spatial resolution has improved with each advance in MDCT technology. Submillimeter resolution has been achieved in MDCT scanners ranging from 16 to 320 slices. The spatial resolution of the present 64-slice MDCT scanners is ≈0.4 mm.[74] This is an improvement over the 0.7-mm resolution of 16-slice MDCT but not as high as can be obtained with catheter-based cine angiography (<0.3 mm).

Contrast Medium Administration

Coronary CTA requires intravenous administration of an iodinated contrast medium. Power injectors are programmed to administer 50 to 160 mL of iodinated contrast medium at a rate of 4 to 6 mL/s through a cannula designed for this injection rate (typically 18 gauge or greater) that is usually placed in an antecubital vein. Accurate timing of the CT scan relative to the start of the contrast injection is the major determinant of overall image quality and enhancement of the coronary arteries. To optimize this timing, a test bolus of 10 to 20 mL of contrast medium can be injected to measure the time to peak enhancement of the aortic root; this time period is then programmed into the MDCT scanner when the coronary CTA is performed. Alternatively, the CT scanner can be set to automatically initiate scanning when the enhancement of the aortic root exceeds a predetermined threshold.

The volume of intravenous contrast medium required for coronary CTA is proportional to the injection rate chosen and the duration of the CT scan. Approximately 60 to 100 mL of contrast medium is injected for coronary CTA with present MDCT scanners.

Pharmacological Patient Preparation

Because of the limited temporal resolution of MDCT scanners, low heart rates are desirable to avoid motion artifacts.[75–78] Several studies have convincingly shown that lowering the heart rate to 60 beats per minute or less by oral administration of β-receptor blocking agents 60 to 90 minutes before the scan, or intravenous administration immediately before the scan, or both, can decrease the frequency and extent of motion artifacts on the coronary CTA scan[75,79] by prolonging the rest period (the time during the cardiac cycle at which coronary artery velocity is low).[80] Image quality on lower temporal resolution MDCT scanners reveals the greater benefit of lower heart rates. For example, for scanners with a temporal resolution of ≥250 ms, a heart rate of <60 beats per minute is needed to minimize coronary motion artifacts.[75,79] For scanners with a temporal resolution of at least 167 ms, a heart rate of ≤75 beats per minute results in acceptable image quality.[81] For new dual-source CT scanners, acceptable image quality of the coronary arteries has been obtained at up to 90 beats per minute.[82] Therefore, pharmacological heart-rate control may not be necessary for many of the patients who undergo coronary CTA on dual-source scanners.

Some investigators and practitioners of coronary CTA administer sublingual nitroglycerin immediately before the scan to achieve vasodilatation.[83] The use of nitroglycerin has been shown to improve image quality in one small study performed using 16-slice MDCT.[83]

Radiation Dose

Coronary CTA can expose a patient to considerably higher amounts of ionizing radiation than standard radiographs, CT calcium scoring, or x-ray angiography.[84] The reasons for the higher radiation dose are that continuous x-ray irradiation occurs during the entire 8- to 20-second MDCT scan, and this is coupled with overlapping slices and specific requirements for x-ray tube current and voltage. To maintain low levels of image noise and thus high image quality, x-ray tube current (mA) and tube voltage (kVp) must be increased with increasing patient body size or decreasing slice thickness or scan time. For a given slice thickness, radiation dose increases linearly with tube current and by the square of the ratio between the original and increased tube voltage setting.[85]

The radiation doses for coronary CTA reported in the literature vary, mostly because of technical differences between scanner generations (eg, 16 versus 64 slice) and between scanners from various manufacturers. The most meaningful parameters of CT dosimetry are the volume CT dose index ($CTDI_{vol}$) and the effective dose (E). The $CTDI_{vol}$, expressed in SI units of milliGray (mGy),[86] represents the average radiation dose over the center slice of a CT scan and is useful for comparing absorbed radiation doses from different CT scanning protocols. The $CTDI_{vol}$ value increases with decreasing pitch (defined as the patient-table advance relative to the width of all simultaneously acquired slices and not relative to the width of a single slice). The $CTDI_{vol}$ is typically displayed on the CT scanner console once an imaging protocol has been loaded. E is the radiation dose parameter most frequently reported in the coronary CTA literature and is expressed in SI units of milliSievert (mSv).[87,88] E cannot be

measured but is a rough estimate of the biological risk of a partial body exposure relative to an equivalent whole-body radiation exposure. E is typically used to analyze population dose rather than individual patient dose. The use of E allows comparisons between the biological effects of exposure to ionizing radiation from various sources and is not limited to medical imaging. There are several techniques for estimating E, and these are generally in good agreement.[87,88] Some models report a gender-specific E, whereas others average radiation doses between both genders. At present, the way that effective dose quantitatively translates into a lifetime risk of malignancies in subjects exposed to ionizing radiation is a controversial topic.[89]

In general, radiation dose increases with increasing number and thinner collimation of slices acquired simultaneously during each gantry rotation, because of detector inefficiency in the presence of a broader x-ray beam and higher photon requirements to keep image noise constant if slice thickness is reduced. E values for vendor-recommended MDCT coronary angiography scanning protocols range from 10.9 mSv for male patients and 13.0 mSv for female patients with use of a 4-slice scanner[90] to 13.0 mSv averaged between male and female patients with a 16-slice scanner.[85] For comparison, an individual receives an ≈3 mSv radiation dose each year from natural background radiation,[91] 0.05 mSv for a chest x-ray, and ≈5 to 6 mSv for a diagnostic x-ray coronary angiogram.[92] With present technology, use of MDCT coronary CTA in a population that is at very low risk for coronary artery disease is inappropriate, because the risk associated with the radiation exposure may exceed the potential benefit of the CTA.[93]

Radiation dose from coronary CTA can be reduced by using several techniques, not all of which are available on every MDCT scanner on the market. One technique, termed ECG-controlled tube-current modulation, decreases x-ray tube current during systole. Because coronary CTA images are typically reconstructed from data acquired during diastole, image quality is maintained particularly for lower heart rates.[94–96] ECG-controlled tube-current modulation decreases radiation dose by 25% to 45%, depending on the patient's heart rate during the scan.[85,94,95,97] A second method for radiation dose reduction is to reduce the x-ray tube current while scanning in the anterior-posterior plane compared with when scanning through the lateral plane.[98,99]

In recent clinical studies of 64-slice MDCT coronary CTA, E has ranged from ≈10 to 14 mSv with ECG-triggered tube-current modulation[100] to 13 to 15 mSv for men and 18 to 21 mSv for women without tube-current modulation.[101,102] In a study of 1035 patients undergoing coronary CTA with tube-current modulation, radiation dose estimates were 6±2 and 11±4 mSv for 16- and 64-slice CTA, respectively.[103] Using higher pitch and greater time per cardiac cycle during which tube current is reduced by tube-current modulation may substantially reduce the radiation dose received from coronary CTA with dual-source CT scanners.[73]

CTA Applications

Anomalous Coronary Artery

Multiple published series exist[104–109] of patients who underwent comparison of coronary CTA data with x-ray angiography (Table 5) for anomalous coronary artery evaluation. The assessment of anomalous coronary origin via cardiac CT has been shown to be accurate[110–112] and of benefit in detecting and characterizing anomalous coronary artery compared with x-ray angiography.[106]

Table 5. Coronary CTA for Anomalous Coronary Artery Evaluation

Reference	No. of Patients	Correctly Classified Anomalous Vessels, n (%)
Schmid et al[104]	35	35 (100)
Datta et al[105]	18	20 (100)
Schmitt et al[106]	44	44 (100)*
Sato et al[107]	5	5 (100)
Shi et al[108]	16	16 (100)
van Ooijen et al[109]	13	13 (100)
Ropers et al[112]	30	29 (97)

*Numbers include 9 patients who could not be classified with x-ray angiography.

Coronary CTA for Identification of Native Vessel Coronary Stenoses

The feasibility of coronary CTA was initially demonstrated with 4-slice MDCT.[52,63,97–106] However, image evaluation was impaired in many cases owing to limited spatial and temporal resolution. With the introduction of 16-slice MDCT, image quality in coronary CTA has become more consistent. The minimal technical prerequisite for contrast-enhanced MDCT coronary CTA is 16-slice technology with a gantry rotation time of <500 ms and slice collimation of <1.0 mm. Several studies have been published that demonstrated substantially improved image quality over previous scanner generations[113] and generally improved accuracy for the detection of coronary artery stenoses (sensitivity of 30% to 98% and specificity of 86% to 98%, Table 6).[97,114–127] Studies that used 16-slice acquisition and rotation times of <400 ms have reported sensitivities between 83% and 98% as well as specificities between 96% and 98%.[117,121–127]

Shorter examination times are possible with 64-slice MDCT; these scanners also frequently incorporate improved temporal and spatial resolution compared with 16-slice MDCT. To date, the sensitivity and specificity of MDCT studies range from 73% to 100% and 91% to 97%,[100–102,128–131] respectively (Table 6). Meta-analyses of 64-slice MDCT studies arrived at sensitivities of 93% and specificity of 96%[132] (in 6 studies) and sensitivities of 86% and specificity of 96%[133] (in 19 studies).

Studies to evaluate the accuracy of coronary CTA for stenosis detection have been limited by relatively small patient groups. In early studies, patients were excluded from enrollment (eg, patients with arrhythmias); also, nonevaluable segments were often excluded from analysis. These exclusions limit the applicability of the reported results to the clinical situation.

Detection of in-stent restenosis has been challenging with 16-slice MDCT, because artifacts caused by stent material frequently preclude adequate visualization of the stent lumen. In 5 small studies that compared coronary CTA to invasive

Table 6. CTA for the Detection of Coronary Artery Stenosis

Reference	Technique	No. of Patients	Not Evaluable, %	Sensitivity, %	Specificity, %	Negative Predictive Value, %	Remarks
Nieman et al[114]	16-slice CT	59	7	95	86	97	Per-artery analysis, all segments >2.0 mm
Ropers et al[115]	16-slice CT	77	12	93	92	97	Per-artery analysis, all segments >1.5 mm
Kuettner et al[116]	16-slice CT	58	...	72 to 98*	97 to 98*	97 to 100*	Per-segment analysis, all of 13 segments (in patients with Agatston score <1000*)
Mollet et al[97]	16-slice CT	128	...	92	95	98	Per-segment analysis, all segments >2.0 mm
Martuscelli et al[117]	16-slice CT	64	16	89	98	98	Per-segment analysis, all segments >1.5 mm
Hoffmann et al[118]	16-slice CT	33	...	63 to 89*	95 to 96*	96 to 97*	Per-segment analysis, all of 17 segments (proximal and mid segments*)
Fine et al[119]	16-slice CT	50	2	87	97	98	Per-segment analysis, all segments >1.5 mm
Kaiser et al[120]	16-slice CT	140	23	30	9	83	Per-segment analysis, all segments
Aviram et al[121]	16-slice CT	22	...	86	98	98	Per-segment analysis, all segments >1.5 mm
Kuettner et al[122]	16-slice CT	72	7	82	98	97	Per-segment analysis, all of 13 segments
Mollet et al[123]	16-slice CT	51	...	95	98	99	Per-segment analysis, all segments >1.5 mm
Schuijf et al[124]	16-slice CT	45	6	98	97	100	Per-segment analysis, all segments
Hoffmann et al[125]	16-slice CT	103	6	95	98	99	Per-segment analysis, all segments >1.5 mm
Morgan-Hughes et al[126]	16-slice CT	58	2 to 37*	83 to 89*	97 to 98*	97 to 99*	Per-segment analysis, all of 15 segments (in patients with Agatston score <400*)
Achenbach et al[127]	16-slice CT	50	4	94	96	99	Per-segment analysis, all segments >1.5 mm
Garcia et al[222]	16-slice CT	187	29	85	91	99	Per-segment analysis, all segments >2.0 mm
Cordeiro et al[223]	32-slice CT	30	20	76	94	96	Per-artery analysis in patients with previously known coronary artery disease, all segments >2.0 mm
Leschka et al[130]	64-slice CT	67	...	94	97	99	Per-segment analysis, all segments ≥1.5 mm
Leber et al[100]	64-slice CT	59	7	73	97	99	Per-segment analysis, segments without severe motion artifact and vessel contrast to noise ≥4
Ehara et al[128]	64-slice CT	69	8	90	94	95	Per-segment analysis, segments without severe motion artifact
Raff et al[102]	64-slice CT	70	12	86	95	98	Per-segment analysis, all segments ≥1.5 mm
Fine et al[129]	64-slice CT	66	4	95	96	92	Per-artery analysis, all arteries ≥1.5 mm
Ropers et al[131]	64-slice CT	82	4	95	93	99	Per-segment analysis, all segments ≥1.5 mm
Mollet et al[101]	64-slice CT	52	2	99	95	99	Per-segment analysis, 15-segment model
Nikolaou et al[224]	64-slice CT	72	10	86	95	97	Per-segment analysis, all segments >1.5 mm
Schlosser et al[225]	64-slice CT	61	...	100	95	100	Per-segment analysis, unevaluable segments considered stenotic
Muhlenbruch et al[226]	64-slice CT	51	...	87	95	98	Per-segment analysis
Meijboom et al[227]	64-slice CT	104	...	92	91	99	Per-segment analysis
Schuijf et al[228]	64-slice CT	60	...	85	98	99	Per-segment analysis

(*Continued*)

Table 6. Continued

Reference	Technique	No. of Patients	Not Evaluable, %	Sensitivity, %	Specificity, %	Negative Predictive Value, %	Remarks
Oncel et al[229]	64-slice CT	80	...	96	98	99	Per-segment analysis
Herzog et al[230]	64-slice CT	50	...	89	92	97	Per-segment analysis
Ehara et al[231]	64-slice CT	69	8	90	94	95	Per-segment analysis
Shabestari et al[232]	64-slice CT	143	2	94	97	97	Per-vessel analysis
Cademartiri et al[233]	64-slice CT	72	0	100	98.6	100	Per-segment analysis
Hausleiter et al[234]	64-slice CT	114	8	92	92	99	Per-segment analysis, unevaluable segments considered stenotic
Meijboom et al[235]	64-slice CT	254	...	88	94	99	Per-segment analysis
Andreini et al[236]	64-slice CT	200	3	99	96	100	Per-segment analysis
Pundziute et al[237]	64-slice CT dual source	103	3	97	91	98	Per-segment analysis
Weustink et al[238]	64-slice CT dual source	100	...	95	95	99	Per-segment analysis
Leber et al[239]	64-slice CT dual source	90	...	90	98	99	Per-segment analysis
Scheffel et al[240]	64-slice CT dual source	30	...	96	98	99	Per-segment analysis
Oncel et al[241]	64-slice CT dual source	15	6-7	80-87	98-99	99	Per-segment analysis in patients with atrial fibrillation
Johnson et al[242]	64-slice CT dual source	35	2	88	98	99	Per-segment analysis in patients with atrial fibrillation
Ropers et al[243]	64-slice CT dual source	100	4	90	98	99	Per-segment analysis in patients with atrial fibrillation
Heuschmid et al[244]	64-slice CT dual source	51	18.5	96	87	99	Per-segment analysis

*Sensitivity, specificity, and negative predictive value based on luminal stenosis >50% in evaluable segments.

angiography, sensitivity for detection of in-stent restenosis by 16- and 40-slice MDCT was 54% to 100%.[134,135] Up to 49% of stents were not evaluable.[135–139] One study that assessed only stents implanted in the left main coronary artery (mean stent diameter 3.9 mm) found 4 of 4 stent restenoses.[134] A recent study performed by 64-slice CT in 64 patients with 102 stents demonstrated that only 58% of stents were evaluable by CT. In evaluable stents, sensitivity and specificity for detection of in-stent stenosis was 86% and 98%.[140] However, in this and other studies, a substantial influence of stent size and material, as well as of CT system specifications and image acquisition and reconstruction protocols used on stent visibility has been documented.[141–144] Thus, routine assessment of coronary stents has not been shown to be reliable with present technology.

The presence of hemodynamically relevant coronary artery stenoses in patients without stents and bypass grafts may be ruled out by MDCT with a high negative predictive value (between 98% and 100% in most studies). MDCT for the diagnosis of hemodynamically relevant coronary artery stenoses should be limited to patients who do not have a high pretest probability. In patients with a high pretest probability of coronary stenoses, a clinical benefit of MDCT coronary angiography is unlikely, given the increased likelihood that interventional treatment (invasive angiography or bypass surgery) will be necessary. In the case of equivocal stress-test results, it is conceivable but unproven that MDCT coronary CTA may facilitate a decision for or against invasive coronary angiography. Screening of asymptomatic individuals concerning the presence of coronary artery stenoses is not justified at present.

Coronary CTA for Coronary Artery Bypass Graft Assessment

Occlusion and patency of arterial and venous bypass grafts can be assessed with high accuracy (sensitivity of 100% for detection of bypass occlusion in 3 studies performed with 16-slice MDCT). However, the detection of coronary stenoses at the anastomotic site and in the native coronary arteries after bypass surgery has been difficult with both 16-slice[145–153] and 64-slice systems.[154] Specifically, overestimation of coronary obstruction has been reported in the presence of coronary calcification[154] (Table 7).

Limitations of Coronary CTA and MRA

Coronary MRA and CTA are purely diagnostic tests that do not provide an option for immediate intervention and do not presently serve as the only basis for performing coronary artery bypass surgery. No outcomes-based analysis has been performed to establish the usefulness of either modality in a given clinical situation. The published comparisons between coronary CTA and MRA on one hand and catheter-based angiography on the other have generally comprised relatively

Table 7. Evaluation of Coronary Artery Bypass Graft Occlusion and Patency by 16-Slice and 64-Slice Coronary CTA

		Bypass Occlusion			Bypass Stenosis		
Reference	No. of Patients	Sensitivity, %*	Specificity, %*	Not Evaluable, %	Sensitivity, %*	Specificity, %*	Not Evaluable, %
Nieman et al[146]	24	100	98	0 to 5	60 to 83	88 to 90	5 to 10
Martuscelli et al[145]	96	100	100	9 to 12	90	100	9 to 12
Schlosser et al[147]	51	100	100	12	90	100	12
Chiurlia et al[150]	51	100	100	0	96	100	0
Moore et al[151]	50	100	100	0	100	99	0
Burgstahler et al[149]	13	100	100	5	100	93	0
Salm et al[153]	25	100	100	8	100	94	8
Anders et al[148]	32	100	98	0	75 to 100	92 to 93	16
Pache et al[152]	31	100	100	3	98	98	3
Malagutti et al[154]	52	99†	96†	0†	...	...	...
Meyer et al[245]	138	97	97	2	...	...	...
Onuma et al[246]	54	100	100	...	100	98	5
Feuchtner et al[247]	41	85	95	...	...	...	...
Ropers et al[248]	50	100	94	0	...	...	...

*Sensitivity and specificity based on luminal stenosis >50%.
†Analysis of graft stenosis and graft occlusion combined.

small groups of patients who were preselected to undergo angiography as well as CTA or MRA.

A technical limitation of both CTA and MRA is lower spatial resolution than is possible with invasive angiography. It has not been consistently shown that either method accurately grades the degree of luminal narrowing within coronary artery lesions. Because the temporal resolution is low, motion artifacts can occur that cause false-negative and false-positive findings. Other image artifacts can be introduced by the patient's inability to follow breathing commands, involuntary motion of the diaphragm, and arrhythmias that occur during the CTA or MRA scan. Continuous visualization of the coronary arteries is not possible at present in patients with atrial fibrillation or frequent ectopy.

Potential risks associated with coronary CTA and MRA include the use of sublingual nitroglycerin as well as pharmacological control of heart rate for CTA. The image quality of coronary CTA has been shown to benefit by the administration of β-blocker therapy to slow the heart rate. The potential for patient self-referral for coronary CTA or MRA without knowledge of its benefits versus risks expands questions of risk assessment into the public health and policy arena.[155]

Limitations Specific to Coronary MRA

Relative to invasive angiography as well as coronary CTA, the spatial resolution of MRA is significantly lower. This lower spatial resolution, along with the necessity to average data from several cardiac cycles to form an image, is probably one of the primary reasons for the generally lower reported sensitivity and specificity of coronary MRA compared with CTA (Tables 2 through 6). However, one recent direct comparison of MRA and 16-slice MDCT coronary CTA showed similar sensitivity (75% versus 82%, respectively) and specificity (77% versus 79%, respectively)[47] despite these acknowledged differences in spatial resolution between the two methods.

The techniques for coronary MRA vary based on the MR vendor and software availability. Coronary MRA may not be widely available, particularly at community imaging centers. Patients who have implanted electronic devices such as internal defibrillators are generally excluded from receiving MR imaging. Metal in the chest from sternal wires or from coronary stents may preclude visualization of coronary arteries near the metal. Claustrophobia occurs in 1% to 5% of patients who undergo MR imaging. This can be controlled by the administration of anxiolytics, but substantially altered breathing patterns and reduced ability to cooperate may negatively affect the quality of the examination. Nondiagnostic MRA examinations may occur in patients with highly irregular breathing patterns. Coronary MRA examination time in experienced labs should be ≈30 minutes using a 2D breath-hold strategy. Using 3D whole-heart imaging, similar scanning times are reported.

Limitations Specific to Coronary CTA

Calcifications within the coronary arteries can cause false-negative and, more frequently, false-positive findings[118] concerning the presence of coronary artery stenosis. Coronary artery segments with substantial calcification may not be evaluable with respect to the presence of a hemodynamically relevant stenosis. The coronary lumen is generally not well observed in the region of a coronary stent.

Coronary CTA requires intravenous injection of iodinated contrast media. Because patients may subsequently require invasive angiography, those with compromised renal function are generally excluded from coronary CTA. In addition to nephrotoxicity, intravenous administration of iodinated contrast media may also be associated with anaphylactoid reaction.[156–161]

Table 8. Reporting of Coronary CTA and MRA Results

Indication for examination
Imaging technique used
Administration of contrast agents (type, dose, route)
Vasodilator or β-blocker
Workstation methods for image reconstruction
Complications
Description of findings
Overall description of image quality/diagnostic confidence
Anomalies of coronary origin
Right or left dominant system
Location and size of any coronary artery aneurysm/dilatation
Description of atherosclerotic narrowing for vessels ≥2 mm in diameter (CTA)
Location of atherosclerotic narrowing by anatomic landmarks
Diffuse or focal disease description
15-Segment model may be used for description
Noncardiac findings (eg, adjacent lung fields, aorta)
Ventricular size and function when requested if appropriate software is available
Limitations of the examination
Heavy calcification (CTA)
Motion abnormalities, arrhythmia
Difficulties with contrast injection
Summary statement/impression and recommendation

The predominant risk of coronary CTA is radiation exposure (as discussed in Radiation Dose). Recent improvements in spatial and temporal resolution of MDCT have made coronary CTA feasible in infants and children, particularly for delineation of anomalous coronary artery origin and course. However, the projected lifetime cancer mortality that is attributable to radiation exposure from CT is significantly higher in children than in adults.[162] Bismuth-coated latex shielding placed over breast tissue has been suggested to decrease breast radiation exposure by 40% without significant image degradation during CT of female children.[163] High heart rates and the potential need for sedation further complicate the expansion of MDCT to the pediatric population.

Reporting of Coronary CTA and MRA Results

The coronary CTA or MRA report (Table 8) should provide as much information as possible using terminology similar to that used in the reporting of catheter-based angiography. Compared with MRA, coronary CTA is more frequently performed for clinical evaluation of atherosclerotic coronary artery disease. Coronary CTA can assess the presence of noncalcified and calcified coronary artery plaque, whereas coronary MRA cannot easily differentiate between the two. Although the additional performance of high-resolution imaging of the coronary artery wall may assist in plaque-component characterization,[164] this technique is still in its infancy.

A comment should be made in the report regarding the technical quality of the examination, especially if it is poor or adversely affected by respiratory motion, cardiac motion, or poor contrast opacification. Unlike x-ray angiography, both CTA and MRA examinations will image the valves, great arteries, myocardium, pericardium, and adjacent lung tissue. A comment should be made in the report if an abnormality in these surrounding structures is present.

In reporting results of both coronary CTA and MRA, the physician should comment on the origin and course of the epicardial vessels. Particular mention should be made if the origin or course of an artery is anomalous. In addition, comment should be made as to whether the coronary artery system is right or left dominant. This may be determined by identifying whether the posterior descending artery and left posterior ventricular branch receive blood supply from the right (RCA) or left (usually left circumflex [LCX]) coronary artery system or both.

The report should state the presence, location, and size of any coronary artery aneurysmal or pseudoaneurysmal dilatations. The location and patency of coronary artery bypass grafts can be assessed with either method,[150,165] and this information should be reported.

For coronary CTA, vessels of ≥1.5 to 2 mm in diameter can be assessed for atherosclerotic narrowing.[166] Reporting should include all coronary arteries of this size, including epicardial vessels (left main, left anterior descending, left circumflex, RCA) and their branches (diagonals, obtuse marginals, left posterior ventricular branch, posterior descending artery, etc).

Images of the coronary arteries should be assessed on a workstation that allows for interactive manipulation and postprocessing of the acquired data set. Images should first be assessed on the transversely acquired source images, and the presence and location of coronary artery atherosclerosis should be noted. Most studies have used combinations of at least 2 types of image displays.[167,168] Coronary arteries should be assessed by multiplanar reformations or curved multiplanar reformations perpendicular to one another at the vessel center. Thin maximum-intensity projection images may be useful for assessment but should not be the only data assessed for reporting purposes given the potential for missing coronary lesions due to overlapping high-density structures that may obscure lumen narrowing.

The location of the atherosclerotic lesions, namely, proximal, mid-, and distal for the RCA, and by anatomic landmarks for the left anterior descending and left circumflex arteries (ie, just prior to first diagonal), should be described in addition to whether the disease is diffuse or focal. For x-ray angiography, some investigators have described using a 15-segment model,[169] and this reporting design may be used for coronary CTA.

With coronary CTA, images may also be reconstructed to obtain accurate functional cardiac information,[170] such as left ventricular end-diastolic volume, end-systolic volume, and ejection fraction. This information may be helpful to the clinician and may be included if the analysis software for this purpose is available.

Future Directions in Noninvasive Coronary Artery Imaging With CT and Magnetic Resonance Imaging

Imaging of Atherosclerotic Plaque

Catheter-based angiographic studies have shown that myocardial infarction may result from rupture of a vulnerable

plaque in the absence of a significant luminal stenosis. Other markers of vulnerability include presence of inflammatory cells, a thin fibrous cap, and a large lipid core.[159–163] These rupture-prone plaques, which are 7 times more likely to ulcerate than the more severe, extensive plaques, are not visible on 2D x-ray angiography.[171,172] Thus, techniques for noninvasive imaging of atherosclerotic plaque with MR or CT have been of great interest.

The likelihood of plaque rupture is based on plaque composition rather than plaque volume.[171,173] It has been observed that unstable plaques are generally higher in lipid content than stable plaques. Most ruptures occur in plaques containing a soft, lipid-rich core covered by a thin, inflamed fibrous cap.[174] A thin fibrous cap is on the order of 70 μm, which is 10 times beyond the present in-plane resolution of MDCT (750 μm) and magnetic resonance imaging (MRI; 500 to 780 μm).[175]

Noncalcific Plaque Detection With Coronary CTA

Improved spatial and temporal image acquisition with submillimeter slice collimation has facilitated atherosclerotic plaque detection via MDCT. Preliminary studies suggest that CT has the potential to distinguish between fat tissue, fibrous tissue, and calcium. The lowest CT density values correlate well with lipid-laden plaque on intravascular ultrasound (IVUS), whereas intermediate densities correlate with fibrous lesions. However, overlap between densities makes distinction between fibrous and soft plaques more problematic.[176] At present, assessment of noncalcified plaque remains limited to studies of very high image quality and may not pertain to average clinical applications.[177–179]

CT technology has been compared with intravascular ultrasound in the classification of plaque composition with cardiac CT.[177,180–184] In the largest MDCT study that evaluated 875 coronary segments, sensitivity values for hypoechoic, hyperechoic, and calcific plaques were 78%, 78%, and 95%, respectively, whereas specificity was 92%.[181] However, this study demonstrated that optimal diagnostic image quality was not obtained for 15% of coronary vessels. The investigators also conceded that noncalcific plaque visualization is limited by plaque and vessel size. The smaller plaques located in smaller coronary sections were not accurately characterized. Advances in spatial resolution in future generations of CT may help overcome these limitations.

Quantification of coronary atherosclerotic plaque burden using CT technology is presently limited. In the study by Achenbach et al,[177] MDCT substantially underestimated plaque volume per segment as compared with IVUS (24±35 versus 43±60 mm^3, $P<0.001$). In other comparisons between MDCT and IVUS, plaque areas showed moderate correlation ($r=0.55$) between the two methods, with a significant tendency toward overestimation by MDCT (8.3±4.8 versus 7.3±3.1 mm^3, $P<0.001$).[185] Plaque volumes in the proximal coronary arteries were found to correlate significantly between 64-slice MDCT and IVUS, with a correlation coefficient of $r=0.83$.[179] However, interobserver variability for plaque volume measurements by MDCT have been as high as 37%.[179] The Scientific Statement on Cardiac CT published by the American Heart Association discusses the applications of soft-plaque detection and the relationship to calcified plaque.[186]

Noncalcific Plaque Detection With MR

The coronary artery wall may be evaluated with MR using "black-blood" pulse sequences that do not require iodinated contrast media or ionizing radiation.[178,187] Black-blood MR has been used extensively for imaging plaque in the carotid wall.[188–197] At present, the maximum resolution of the method is 500 to 780 μm.

The wall thickness in MR corresponds to intima, media, and adventitial layers, with increased wall thickening in atherosclerosis occurring primarily in the media.[196,198,199] In patient studies, coronary wall MR identified increased coronary artery wall thickness with preservation of lumen size in patients with nonsignificant coronary artery disease, which is consistent with a Glagov type of outward arterial remodeling.[178] MR of coronary arteries in patients with >40% stenosis as assessed by x-ray angiography revealed localized wall thickness; the difference in maximum wall thickness between the normal subjects and patients was statistically significant ($P=0.0001$).[189] Individuals with mild yet angiographically detectable coronary artery disease had a wall thickness as measured by MR of 1.7±0.3 mm; wall thickness in healthy subjects was 1.0±0.2 mm.[178]

Intravascular MR Contrast Agents

Current FDA-approved contrast agents for MR in the United States are extracellular agents that leak rapidly (within seconds) out of the vessel lumen into the extracellular spaces. This leakage reduces enhancement of the vessel lumen. Newer intravascular agents (the so-called blood-pool agents) that are based either on gadolinium (eg, B22956 and MS-325) or iron oxide (eg, AMI 227) have been developed.[18,19,200–202] The use of intravascular agents has the advantage of allowing image acquisition over longer time periods. Because the signal of blood remains relatively constant for a prolonged time after a single injection, navigator approaches or multiple breath-holds can be used after a single injection.[18] Initial results for these contrast agents in improving vessel signal[203,204] and sharpness[203,205] have been reported.

Summary and Recommendations

Noninvasive coronary CTA and MRA represent substantial advances that may ultimately be valuable for diagnosis of significant coronary artery disease. The chief advantages of coronary CTA compared with MRA are wider availability, higher spatial resolution, and more consistent, shorter examinations with better patient adherance. Advantages associated with coronary MRA are a lack of ionizing radiation and a lack of administration of iodinated contrast material. Both tests are presently suboptimal for patients with atrial fibrillation and other arrhythmias, and image quality may be further reduced by high body mass.

Specific recommendations for use of these technologies are expected to change along with advances in scanner hardware and software. At present, the following general statements represent the consensus opinions of the writing group:

Classification of recommendations and levels of evidence are expressed in the American College of Cardiology/American Heart Association (ACC/AHA) format as follows:

- **Class I:** Conditions for which there is evidence for and/or general agreement that the procedure or treatment is beneficial, useful, and effective.
- **Class II:** Conditions for which there is conflicting evidence and/or a divergence of opinion about the usefulness/efficacy of a procedure or treatment.
  - **Class IIa:** Weight of evidence/opinion is in favor of usefulness/efficacy.
  - **Class IIb:** Usefulness/efficacy is less well established by evidence/opinion.
- **Class III:** Conditions for which there is evidence and/or general agreement that the procedure/treatment is not useful/effective and in some cases may be harmful.
- **Level of Evidence A:** Data derived from multiple randomized clinical trials.
- **Level of Evidence B:** Data derived from a single randomized trial or nonrandomized studies.
- **Level of Evidence C:** Only consensus opinion of experts, case studies, or standard of care.

1. Neither coronary CTA nor MRA should be used to screen for coronary artery disease in patients who have no signs or symptoms suggestive of coronary artery disease. (**Class III, level of evidence C**)
2. No multivendor trial data are available for coronary MDCT CTA or for present whole-heart coronary MRA. Thus, the applicability of these methods beyond the reporting research centers is unknown. Ideally, both multivendor and additional multicenter validation of these methods should be performed. (**Class I, level of evidence C**)
3. The potential benefit of noninvasive coronary angiography is likely to be greatest and is reasonable for symptomatic patients who are at intermediate risk for coronary artery disease after initial risk stratification, including patients with equivocal stress-test results. (**Class IIa, level of evidence B**) Diagnostic accuracy favors coronary CTA over MRA for these patients. (**Class I, level of evidence B**) Concerns regarding radiation dose limit the use of coronary CTA in high-risk patients who have a very low pretest likelihood of coronary stenoses; patients with a high pretest likelihood of coronary stenoses are likely to require intervention and invasive catheter angiography for definitive evaluation; thus, CTA is not recommended for those individuals. (**Class III, level of evidence C**) Pronounced coronary calcification may negatively impact interpretability and accuracy of coronary CTA and thus, the usefulness of CTA is uncertain in these individuals. (**Class IIb, level of evidence B**)
4. Anomalous coronary artery evaluation can be performed by either CTA or MRA; radiation-protection concerns indicate that MRA is preferred when it is available. (**Class IIa, level of evidence B**)
5. Reporting of coronary CTA and MRA results should describe any limitations to the technical quality of the examination and the size of the vessels, descriptions of coronary anomalies, coronary stenosis, and significant noncardiac findings within the field of view. (**Class I, level of evidence A**)
6. Continued research in cardiac CT and MR imaging is encouraged to determine the potential of these noncatheter-based modalities to detect, characterize, and measure atherosclerotic plaque burden, as well as its change over time or as the result of therapy. (**Class I, level of evidence C**)

Disclosures

Writing Group Disclosures

Writing Group Member	Employment	Research Grant	Other Research Support	Speakers' Bureau/Honoraria	Ownership Interest	Consultant/Advisory Board	Other
David A. Bluemke	Johns Hopkins University	Toshiba*; Epix Medical*; NIH†	Toshiba*	Toshiba*	None	Berlex†; GE Healthcare*	None
Stephan Achenbach	University of Erlangen	Siemens Medical Solutions†	None	None	None	None	None
Matthew Budoff	Harbor-UCLA	None	None	General Electric*	None	None	None
Thomas C. Gerber	Mayo Clinic, Jacksonville	None	None	None	None	Up To Date*	None
Bernard Gersh	Mayo Foundation	None	None	None	None	None	None
L. David Hillis	UT Health Science Center, San Antonio	None	None	None	None	None	None
W. Gregory Hundley	Wake Forest University School of Medicine	None	Bracco Diagnostics*	None	MRI Cardiac Services*	None	None
Warren J. Manning	Beth Israel Deaconess Medical Center, Harvard Medical	Philips Medical Systems†	None	None	None	None	None

(*Continued*)

Continued

Writing Group Member	Employment	Research Grant	Other Research Support	Speakers' Bureau/Honoraria	Ownership Interest	Consultant/Advisory Board	Other
Beth Feller Printz	Columbia University	None	None	None	None	None	None
Matthias Stuber	Johns Hopkins University	R01 grants: coronary MRI†	None	None	Diagnosoft Inc*	Bracco Diagnostics†; Philips Medical Systems†	None
Pamela K. Woodard	Washington University School of Medicine	GE Healthcare*	Siemens*	GE Healthcare*	None	Covidien*	None

This table represents the relationships of writing group members that may be perceived as actual or reasonably perceived conflicts of interest as reported on the Disclosure Questionnaire, which all members of the writing group are required to complete and submit. A relationship is considered to be "significant" if (a) the person receives $10 000 or more during any 12-month period, or 5% or more of the person's gross income; or (b) the person owns 5% or more of the voting stock or share of the entity, or owns $10 000 or more of the fair market value of the entity. A relationship is considered to be "modest" if it is less than "significant" under the preceding definition.

*Modest.

†Significant.

Reviewer Disclosures

Reviewer	Employment	Research Grant	Other Research Support	Speakers' Bureau/ Honoraria	Expert Witness	Ownership Interest	Consultant/Advisory Board	Other
Samuel S. Gidding	A. I. duPont Hospital for Children	None	None	Brown University*	None	None	None	None
Glenn N. Levine	Baylor College of Medicine	None	None	None	None	None	None	None
Gerald Pohost	University of Southern California	None	None	None	None	None	None	None
E. Kent Yucel	Veterans Administration	None	None	None	None	None	None	None

This table represents the relationships of reviewers that may be perceived as actual or reasonably perceived conflicts of interest as reported on the Disclosure Questionnaire, which all reviewers are required to complete and submit. A relationship is considered to be "significant" if (a) the person receives $10 000 or more during any 12-month period, or 5% or more of the person's gross income; or (b) the person owns 5% or more of the voting stock or share of the entity, or owns $10 000 or more of the fair market value of the entity. A relationship is considered to be "modest" if it is less than "significant" under the preceding definition.

*Modest.

References

1. Ammann P, Brunner-La Rocca HP, Angehrn W, Roelli H, Sagmeister M, Rickli H. Procedural complications following diagnostic coronary angiography are related to the operator's experience and the catheter size. *Catheter Cardiovasc Interv*. 2003;59:13–18.
2. Batyraliev T, Ayalp MR, Sercelik A, Karben Z, Dinler G, Besnili F, Ozgul S, Perchucov I. Complications of cardiac catheterization: a single-center study. *Angiology*. 2005;56:75–80.
3. Chandrasekar B, Doucet S, Bilodeau L, Crepeau J, deGuise P, Gregoire J, Gallo R, Cote G, Bonan R, Joyal M, Gosselin G, Tanguay JF, Dyrda I, Bois M, Pasternac A. Complications of cardiac catheterization in the current era: a single-center experience. *Catheter Cardiovasc Interv*. 2001;52:289–295.
4. Foo TK, Ho VB, Saranathan M, Cheng LQ, Sakuma H, Kraitchman DL, Wu KC, Bluemke DA. Feasibility of integrating high-spatial-resolution 3D breath-hold coronary MR angiography with myocardial perfusion and viability examinations. *Radiology*. 2005;235:1025–1030.
5. Danias PG, Stuber M, Botnar RM, Kissinger KV, Chuang ML, Manning WJ. Navigator assessment of breath-hold duration: impact of supplemental oxygen and hyperventilation. *AJR Am J Roentgenol*. 1998;171:395–397.
6. Liu YL, Riederer SJ, Rossman PJ, Grimm RC, Debbins JP, Ehman RL. A monitoring, feedback, and triggering system for reproducible breath-hold MR imaging. *Magn Reson Med*. 1993;30:507–511.
7. Wang Y, Grimm RC, Rossman PJ, Debbins JP, Riederer SJ, Ehman RL. 3D coronary MR angiography in multiple breath-holds using a respiratory feedback monitor. *Magn Reson Med*. 1995;34:11–16.
8. Ehman RL, Felmlee JP. Adaptive technique for high-definition MR imaging of moving structures. *Radiology*. 1989;173:255–263.
9. McConnell MV, Khasgiwala VC, Savord BJ, Chen MH, Chuang ML, Edelman RR, Manning WJ. Prospective adaptive navigator correction for breath-hold MR coronary angiography. *Magn Reson Med*. 1997;37:148–152.
10. Danias PG, McConnell MV, Khasgiwala VC, Chuang ML, Edelman RR, Manning WJ. Prospective navigator correction of image position for coronary MR angiography. *Radiology*. 1997;203:733–736.
11. Stuber M, Botnar RM, Danias PG, Kissinger KV, Manning WJ. Submillimeter three-dimensional coronary MR angiography with real-time navigator correction: comparison of navigator locations. *Radiology*. 1999;212:579–587.
12. Stuber M, Botnar RM, Danias PG, Sodickson DK, Kissinger KV, Van Cauteren M, De Becker J, Manning WJ. Double-oblique free-breathing high resolution three-dimensional coronary magnetic resonance angiography. *J Am Coll Cardiol*. 1999;34:524–531.
13. Spuentrup E, Stuber M, Botnar RM, Manning WJ. The impact of navigator timing parameters and navigator spatial resolution on 3D coronary magnetic resonance angiography. *J Magn Reson Imaging*. 2001;14:311–318.
14. Edelman RR, Manning WJ, Burstein D, Paulin S. Coronary arteries: breath-hold MR angiography. *Radiology*. 1991;181:641–643.
15. Li D, Paschal CB, Haacke EM, Adler LP. Coronary arteries: three-dimensional MR imaging with fat saturation and magnetization transfer contrast. *Radiology*. 1993;187:401–406.
16. Brittain JH, Hu BS, Wright GA, Meyer CH, Macovski A, Nishimura DG. Coronary angiography with magnetization-prepared T2 contrast. *Magn Reson Med*. 1995;33:689–696.
17. Botnar RM, Stuber M, Danias PG, Kissinger KV, Manning WJ. Improved coronary artery definition with T2-weighted, free-breathing, three-dimensional coronary MRA. *Circulation*. 1999;99:3139–3148.

18. Stuber M, Botnar RM, Danias PG, McConnell MV, Kissinger KV, Yucel EK, Manning WJ. Contrast agent-enhanced, free-breathing, three-dimensional coronary magnetic resonance angiography. *J Magn Reson Imaging*. 1999;10:790–799.
19. Hofman MB, Henson RE, Kovács SJ, Fischer SE, Lauffer RB, Adzamli K, De Becker J, Wickline SA, Lorenz CH. Blood pool agent strongly improves 3D magnetic resonance coronary angiography using an inversion pre-pulse. *Magn Reson Med*. 1999;41:360–367.
20. Goldfarb JW, Edelman RR. Coronary arteries: breath-hold, gadolinium-enhanced, three-dimensional MR angiography. *Radiology*. 1998;206: 830–834.
21. Deshpande VS, Shea SM, Laub G, Simonetti OP, Finn JP, Li D. 3D magnetization-prepared true-FISP: a new technique for imaging coronary arteries. *Magn Reson Med*. 2001;46:494–502.
22. Spuentrup E, Buecker A, Stuber M, Botnar R, Nguyen TH, Börnert P, Kölker C, Günther RW. Navigator-gated coronary magnetic resonance angiography using steady-state-free-precession: comparison to standard T2-prepared gradient-echo and spiral imaging. *Invest Radiol*. 2003;38: 263–268.
23. Moran PR. A flow velocity zeugmatographic interlace for NMR imaging in humans. *Magn Reson Imaging*. 1982;1:197–203.
24. Firmin DN, Nayler GL, Kilner PJ, Longmore DB. The application of phase shifts in NMR for flow measurement. *Magn Reson Med*. 1990; 14:230–241.
25. Sakuma H, Blake LM, Amidon TM, O'Sullivan M, Szolar DH, Furber AP, Bernstein MA, Foo TK, Higgins CB. Coronary flow reserve: non-invasive measurement in humans with breath-hold velocity-encoded cine MR imaging. *Radiology*. 1996;198:745–750.
26. Weiger M, Pruessmann KP, Boesiger P. Cardiac real-time imaging using SENSE. SENSitivity Encoding scheme. *Magn Reson Med*. 2000;43: 177–184.
27. Stuber M, Botnar RM, Fischer SE, Lamerichs R, Smink J, Harvey P, Manning WJ. Preliminary report on in vivo coronary MRA at 3 Tesla in humans. *Magn Reson Med*. 2002;48:425–429.
28. Kim WY, Danias PG, Stuber M, Flamm SD, Plein S, Nagel E, Langerak SE, Weber OM, Pedersen EM, Schmidt M, Botnar RM, Manning WJ. Coronary magnetic resonance angiography for the detection of coronary stenoses. *N Engl J Med*. 2001;345:1863–1869.
29. Sakuma H, Ichikawa Y, Suzawa N, Hirano T, Makino K, Koyama N, Van Cauteren M, Takeda K. Assessment of coronary arteries with total study time of less than 30 minutes by using whole-heart coronary MR angiography. *Radiology*. 2005;237:316–321.
30. McConnell MV, Ganz P, Selwyn AP, Li W, Edelman RR, Manning WJ. Identification of anomalous coronary arteries and their anatomic course by magnetic resonance coronary angiography. *Circulation*. 1995;92: 3158–3162.
31. Taylor AM, Thorne SA, Rubens MB, Jhooti P, Keegan J, Gatehouse PD, Wiesmann F, Grothues F, Somerville J, Pennell DJ. Coronary artery imaging in grown up congenital heart disease: complementary role of magnetic resonance and x-ray coronary angiography. *Circulation*. 2000; 101:1670–1678.
32. Post JC, van Rossum AC, Bronzwaer JG, de Cock CC, Hofman MB, Valk J, Visser CA. Magnetic resonance angiography of anomalous coronary arteries. A new gold standard for delineating the proximal course? *Circulation*. 1995;92:3163–3171.
33. Vliegen HW, Doornbos J, de Roos A, Jukema JW, Bekedam MA, van der Wall EE. Value of fast gradient echo magnetic resonance angiography as an adjunct to coronary arteriography in detecting and confirming the course of clinically significant coronary artery anomalies. *Am J Cardiol*. 1997;79:773–776.
34. Machado C, Bhasin S, Soulen RL. Confirmation of anomalous origin of the right coronary artery from the left sinus of Valsalva with magnetic resonance imaging. *Chest*. 1993;104:1284–1286.
35. Doorey AJ, Wills JS, Blasetto J, Goldenberg EM. Usefulness of magnetic resonance imaging for diagnosing an anomalous coronary artery coursing between aorta and pulmonary trunk. *Am J Cardiol*. 1994;74:198–199.
36. Razmi RM, Chun W, Rathi VK, Pohost GM. Coronary magnetic resonance angiography (CMRA): the gold standard for determining the proximal course of anomalous coronary arteries. *J Am Coll Cardiol*. 2001;37:380. Abstract.
37. Bunce NH, Lorenz CH, Keegan J, Lesser J, Reyes EM, Firmin DN, Pennell DJ. Coronary artery anomalies: assessment with free-breathing three-dimensional coronary MR angiography. *Radiology*. 2003;227: 201–208.
38. Greil GF, Stuber M, Botnar RM, Kissinger KV, Geva T, Newburger JW, Manning WJ, Powell AJ. Coronary magnetic resonance angiography in adolescents and young adults with kawasaki disease. *Circulation*. 2002; 105:908–911.
39. Mavrogeni S, Papadopoulos G, Douskou M, Kaklis S, Seimenis I, Baras P, Nikolaidou P, Bakoula C, Karanasios E, Manginas A, Cokkinos DV. Magnetic resonance angiography is equivalent to X-ray coronary angiography for the evaluation of coronary arteries in Kawasaki disease. *J Am Coll Cardiol*. 2004;43:649–652.
40. Newburger JW, Takahashi M, Gerber MA, Gewitz MH, Tani LY, Burns JC, Shulman ST, Bolger AF, Ferrieri P, Baltimore RS, Wilson WR, Baddour LM, Levison ME, Pallasch TJ, Falace DA, Taubert KA. Diagnosis, treatment, and long-term management of Kawasaki disease: a statement for health professionals from the Committee on Rheumatic Fever, Endocarditis, and Kawasaki Disease, Council on Cardiovascular Disease in the Young, American Heart Association. *Pediatrics*. 2004; 114:1708–1733.
41. Mavrogeni SI, Manginas A, Papadakis E, Foussas S, Douskou M, Baras P, Seimenis I, Cokkinos DV. Correlation between magnetic resonance angiography (MRA) and quantitative coronary angiography (QCA) in ectatic coronary vessels. *J Cardiovasc Magn Reson*. 2004;6:17–23.
42. Ichikawa YSH, Makino K, Okano S, Chino S, Hirano T, Takeda K. Diagnostic accuracy of whole heart coronary magnetic resonance angiography for the detection of significant coronary stenoses in patients with suspected coronary artery disease. Paper presented at: 8th Annual Scientific Sessions of the Society for Cardiovascular Magnetic Resonance; January 21 to 23, 2005; San Francisco, Calif.
43. Jahnke C, Paetsch I, Nehrke K, Schnackenburg B, Gebker R, Fleck E, Nagel E. Rapid and complete coronary arterial tree visualization with magnetic resonance imaging: feasibility and diagnostic performance. *Eur Heart J*. 2005;26:2313–2319.
44. Cheng L, Guaricci A, Mulukutla S, Prince MR, Wang Y. Manifestation of coronary stenoses on breath-hold steady state free precession sequences: retrospectively compared to conventional x-ray coronary angiography. *J Cardiovasc Magn Reson*. 2005;117.
45. Dewey M, Teige F, Schnapauff D, Laule M, Borges AC, Rutsch W, Hamm B, Taupitz M. Combination of free-breathing and breathhold steady-state free precession magnetic resonance angiography for detection of coronary artery stenoses. *J Magn Reson Imaging*. 2006;23: 674–681.
46. Sakuma H, Ichikawa Y, Chino S, Hirano T, Makino K, Takeda K. Detection of coronary artery stenosis with whole-heart coronary magnetic resonance angiography. *J Am Coll Cardiol*. 2006;48: 1946–1950.
47. Kefer J, Coche E, Legros G, Pasquet A, Grandin C, Van Beers BE, Vanoverschelde JL, Gerber BL. Head-to-head comparison of three-dimensional navigator-gated magnetic resonance imaging and 16-slice computed tomography to detect coronary artery stenosis in patients. *J Am Coll Cardiol*. 2005;46:92–100.
48. Dewey M, Teige F, Schnapauff D, Laule M, Borges AC, Wernecke KD, Schink T, Baumann G, Rutsch W, Rogalla P, Taupitz M, Hamm B. Noninvasive detection of coronary artery stenoses with multislice computed tomography or magnetic resonance imaging. *Ann Intern Med*. 2006;145:407–415.
49. Hundley WG, Lange RA, Clarke GD, Meshack BM, Payne J, Landau C, McColl R, Sayad DE, Willett DL, Willard JE, Hillis LD, Peshock RM. Assessment of coronary arterial flow and flow reserve in humans with magnetic resonance imaging. *Circulation*. 1996;93:1502–1508.
50. Nagel E, Lehmkuhl HB, Bocksch W, Klein C, Vogel U, Frantz E, Ellmer A, Dreysse S, Fleck E. Noninvasive diagnosis of ischemia-induced wall motion abnormalities with the use of high-dose dobutamine stress MRI: comparison with dobutamine stress echocardiography. *Circulation*. 1999;99:763–770.
51. Hundley WG, Hamilton CA, Clarke GD, Hillis LD, Herrington DM, Lange RA, Applegate RJ, Thomas MS, Payne J, Link KM, Peshock RM. Visualization and functional assessment of proximal and middle left anterior descending coronary stenoses in humans with magnetic resonance imaging. *Circulation*. 1999;99:3248–3254.
52. Hundley WG, Hillis LD, Hamilton CA, Applegate RJ, Herrington DM, Clarke GD, Braden GA, Thomas MS, Lange RA, Peshock RM, Link KM. Assessment of coronary arterial restenosis with phase-contrast magnetic resonance imaging measurements of coronary flow reserve. *Circulation*. 2000;101:2375–2381.
53. Langerak SE, Vliegen HW, Jukema JW, Kunz P, Zwinderman AH, Lamb HJ, van der Wall EE, de Roos A. Value of magnetic resonance

imaging for the noninvasive detection of stenosis in coronary artery bypass grafts and recipient coronary arteries. *Circulation*. 2003;107:1502–1508.
54. Sakuma H, Higgins CB. Magnetic resonance measurement of coronary blood flow. *Acta Paediatr Suppl*. 2004;93:80–85.
55. Nagel E, Thouet T, Klein C, Schalla S, Bornstedt A, Schnackenburg B, Hug J, Wellnhofer E, Fleck E. Noninvasive determination of coronary blood flow velocity with cardiovascular magnetic resonance in patients after stent deployment. *Circulation*. 2003;107:1738–1743.
56. van Geuns RJ, Wielopolski PA, de Bruin HG, Rensing BJ, Hulshoff M, van Ooijen PM, de Feyter PJ, Oudkerk M. MR coronary angiography with breath-hold targeted volumes: preliminary clinical results. *Radiology*. 2000;217:270–277.
57. Goldman S, Copeland J, Moritz T, Henderson W, Zadina K, Ovitt T, Doherty J, Read R, Chesler E, Sako Y. Saphenous vein graft patency 1 year after coronary artery bypass surgery and effects of antiplatelet therapy. Results of a Veterans Administration Cooperative Study. *Circulation*. 1989;80:1190–1197.
58. Fitzgibbon GM, Kafka HP, Leach AJ, Keon WJ, Hooper GD, Burton JR. Coronary bypass graft fate and patient outcome: angiographic follow-up of 5,065 grafts related to survival and reoperation in 1,388 patients during 25 years. *J Am Coll Cardiol*. 1996;28:616–626.
59. White RD, Caputo GR, Mark AS, Modin GW, Higgins CB. Coronary artery bypass graft patency: noninvasive evaluation with MR imaging. *Radiology*. 1987;164:681–686.
60. White RD, Pflugfelder PW, Lipton MJ, Higgins CB. Coronary artery bypass grafts: evaluation of patency with cine MR imaging. *AJR Am J Roentgenol*. 1988;150:1271–1274.
61. Galjee MA, van Rossum AC, Doesburg T, van Eenige MJ, Visser CA. Value of magnetic resonance imaging in assessing patency and function of coronary artery bypass grafts. An angiographically controlled study. *Circulation*. 1996;93:660–666.
62. Aurigemma GP, Reichek N, Axel L, Schiebler M, Harris C, Kressel HY. Noninvasive determination of coronary artery bypass graft patency by cine magnetic resonance imaging. *Circulation*. 1989;80:1595–1602.
63. Engelmann MG, Knez A, von Smekal A, Wintersperger BJ, Huehns TY, Hofling B, Reiser MF, Steinbeck G. Non-invasive coronary bypass graft imaging after multivessel revascularisation. *Int J Cardiol*. 2000;76:65–74.
64. Molinari G, Sardanelli F, Zandrino F, Balbi M, Masperone MA. Value of navigator echo magnetic resonance angiography in detecting occlusion/patency of arterial and venous, single and sequential coronary bypass grafts. *Int J Card Imaging*. 2000;16:149–160.
65. Vrachliotis TG, Bis KG, Aliabadi D, Shetty AN, Safian R, Simonetti O. Contrast-enhanced breath-hold MR angiography for evaluating patency of coronary artery bypass grafts. *AJR Am J Roentgenol*. 1997;168:1073–1080.
66. Wintersperger BJ, Engelmann MG, von Smekal A, Knez A, Penzkofer HV, Höfling B, Laub G, Reiser MF. Patency of coronary bypass grafts: assessment with breath-hold contrast-enhanced MR angiography: value of a non-electrocardiographically triggered technique. *Radiology*. 1998;208:345–351.
67. Bunce NH, Lorenz CH, John AS, Lesser JR, Mohiaddin RH, Pennell DJ. Coronary artery bypass graft patency: assessment with true ast imaging with steady-state precession versus gadolinium-enhanced MR angiography. *Radiology*. 2003;227:440–446.
68. Lu B, Mao SS, Zhuang N, Bakhsheshi H, Yamamoto H, Takasu J, Liu SC, Budoff MJ. Coronary artery motion during the cardiac cycle and optimal ECG triggering for coronary artery imaging. *Invest Radiol*. 2001;36:250–256.
69. Ritchie CJ, Godwin JD, Crawford CR, Stanford W, Anno H, Kim Y. Minimum scan speeds for suppression of motion artifacts in CT. *Radiology*. 1992;185:37–42.
70. Kachelriess M, Kalender WA. Electrocardiogram-correlated image reconstruction from subsecond spiral computed tomography scans of the heart. *Med Phys*. 1998;25:2417–2431.
71. Ohnesorge B, Flohr T, Becker C, Kopp AF, Schoepf UJ, Baum U, Knez A, Klingenbeck-Regn K, Reiser MF. Cardiac imaging by means of electrocardiographically gated multisection spiral CT: initial experience. *Radiology*. 2000;217:564–571.
72. Flohr T, Ohnesorge B. Heart rate adaptive optimization of spatial and temporal resolution for electrocardiogram-gated multislice spiral CT of the heart. *J Comput Assist Tomogr*. 2001;25:907–923.
73. Flohr TG, McCollough CH, Bruder H, Petersilka M, Gruber K, Süss C, Grasruck M, Stierstorfer K, Krauss B, Raupach R, Primak AN, Küttner A, Achenbach S, Becker C, Kopp A, Ohnesorge BM. First performance evaluation of a dual-source CT (DSCT) system. *Eur Radiol*. 2006;16:256–268.
74. Nikolaou K, Becker CR, Muders M, Babaryka G, Scheidler J, Flohr T, Loehrs U, Reiser MF, Fayad ZA. Multidetector-row computed tomography and magnetic resonance imaging of atherosclerotic lesions in human ex vivo coronary arteries. *Atherosclerosis*. 2004;174:243–252.
75. Giesler T, Baum U, Ropers D, Ulzheimer S, Wenkel E, Mennicke M, Bautz W, Kalender WA, Daniel WG, Achenbach S. Noninvasive visualization of coronary arteries using contrast-enhanced multidetector CT: influence of heart rate on image quality and stenosis detection. *AJR Am J Roentgenol*. 2002;179:911–916.
76. Herzog C, Abolmaali N, Balzer JO, Baunach S, Ackermann H, Dogan S, Britten MB, Vogl TJ. Heart-rate-adapted image reconstruction in multidetector-row cardiac CT: influence of physiological and technical prerequisite on image quality. *Eur Radiol*. 2002;12:2670–2678.
77. Hoffmann MH, Shi H, Manzke R, Schmid FT, De Vries L, Grass M, Brambs HJ, Aschoff AJ. Noninvasive coronary angiography with 16-detector row CT: effect of heart rate. *Radiology*. 2005;234:86–97.
78. Schroeder S, Kopp AF, Kuettner A, Burgstahler C, Herdeg C, Heuschmid M, Baumbach A, Claussen CD, Karsch KR, Seipel L. Influence of heart rate on vessel visibility in noninvasive coronary angiography using new multislice computed tomography: experience in 94 patients. *Clin Imaging*. 2002;26:106–111.
79. Gerber TC, Kuzo RS, Lane GE, O'Brien PC, Karstaedt N, Morin RL, Safford RE, Blackshear JL, Pietan JH. Image quality in a standardized algorithm for minimally invasive coronary angiography with multislice spiral computed tomography. *J Comput Assist Tomogr*. 2003;27:62–69.
80. Achenbach S, Ropers D, Holle J, Muschiol G, Daniel WG, Moshage W. In-plane coronary arterial motion velocity: measurement with electron-beam CT. *Radiology*. 2000;216:457–463.
81. Wintersperger BJ, Nikolaou K, von Ziegler F, Johnson T, Rist C, Leber A, Flohr T, Knez A, Reiser MF, Becker CR. Image quality, motion artifacts, and reconstruction timing of 64-slice coronary computed tomography angiography with 0.33-second rotation speed. *Invest Radiol*. 2006;41:436–442.
82. Achenbach S, Ropers D, Kuettner A, Flohr T, Ohnesorge B, Bruder H, Theessen H, Karakaya M, Daniel WG, Bautz W, Kalender WA, Anders K. Contrast-enhanced coronary artery visualization by dual-source computed tomography: initial experience. *Eur J Radiol*. 2006;57:331–335.
83. Dewey M, Hoffmann H, Hamm B. Multislice CT coronary angiography: effect of sublingual nitroglycerine on the diameter of coronary arteries. *Rofo*. 2006;178:600–604.
84. Morin RL, Gerber TC, McCollough CH. Radiation dose in computed tomography of the heart. *Circulation*. 2003;107:917–922.
85. Gerber TC, Stratmann BP, Kuzo RS, Kantor B, Morin RL. Effect of acquisition technique on radiation dose and image quality in multidetector row computed tomography coronary angiography with submillimeter collimation. *Invest Radiol*. 2005;40:556–563.
86. International Electrotechnical Commission. International Standard IEC 60601-2-44 Edition 2.1: Medical Electrical Equipment, Part 2-44: Particular Requirements for the Safety of X-ray Equipment for Computed Tomography. Geneva, Switzerland: International Electrotechnical Commission; 2002.
87. 1990 Recommendations of the International Commission on Radiological Protection. *Ann ICRP*. 1991;21:1–201.
88. McCollough CH, Schueler BA. Calculation of effective dose. *Med Phys*. 2000;27:828–837.
89. Morin RL. What are the national radiation doses? *J Am Coll Radiol*. 2006;3:956.
90. Hunold P, Vogt FM, Schmermund A, Debatin JF, Kerkhoff G, Budde T, Erbel R, Ewen K, Barkhausen J. Radiation exposure during cardiac CT: effective doses at multi-detector row CT and electron-beam CT. *Radiology*. 2003;226:145–152.
91. National Council on Radiation Protection and Measurements. *Report 94: Exposure of the Population in the United States and Canada From Natural Background Radiation*. Bethesda, Md: National Council on Radiation Protection and Measurements; 1987.
92. Coles DR, Smail MA, Negus IS, Wilde P, Oberhoff M, Karsch KR, Baumbach A. Comparison of radiation doses from multislice computed tomography coronary angiography and conventional diagnostic angiography. *J Am Coll Cardiol*. 2006;47:1840–1845.
93. Garcia MJ. Noninvasive coronary angiography: hype or new paradigm? *JAMA*. 2005;293:2531–2533.

94. Jakobs TF, Becker CR, Ohnesorge BM, Schoepf UO, Reiser MF. Tube current modulation for retrospective ECG-gated cardiac-CT. *Radiology*. 2001;221:414.
95. Trabold T, Büchgeister M, Kuttner A, Heuschmid M, Kopp AF, Schröder S, Claussen CD. Estimation of radiation exposure in 16-detector row computed tomography of the heart with retrospective ECG-gating. *Rofo*. 2003;175:1051–1055.
96. Sanz J, Rius T, Kuschnir P, Fuster V, Goldberg J, Ye XY, Wisdom P, Poon M. The importance of end-systole for optimal reconstruction protocol of coronary angiography with 16-slice multidetector computed tomography. *Invest Radiol*. 2005;40:155–163.
97. Mollet NR, Cademartiri F, Nieman K, Saia F, Lemos PA, McFadden EP, Pattynama PM, Serruys PW, Krestin GP, de Feyter PJ. Multislice spiral computed tomography coronary angiography in patients with stable angina pectoris. *J Am Coll Cardiol*. 2004;43:2265–2270.
98. Gies M, Kalender WA, Wolf H, Suess C. Dose reduction in CT by anatomically adapted tube current modulation. I. Simulation studies. *Med Phys*. 1999;26:2235–2247.
99. Kalender WA, Wolf H, Suess C, Gies M, Greess H, Bautz WA. Dose reduction in CT by on-line tube current control: principles and validation on phantoms and cadavers. *Eur Radiol*. 1999;9:323–328.
100. Leber AW, Knez A, von Ziegler F, Becker A, Nikolaou K, Paul S, Wintersperger B, Reiser M, Becker CR, Steinbeck G, Boekstegers P. Quantification of obstructive and nonobstructive coronary lesions by 64-slice computed tomography: a comparative study with quantitative coronary angiography and intravascular ultrasound. *J Am Coll Cardiol*. 2005;46:147–154.
101. Mollet NR, Cademartiri F, van Mieghem CA, Runza G, McFadden EP, Baks T, Serruys PW, Krestin GP, de Feyter PJ. High-resolution spiral computed tomography coronary angiography in patients referred for diagnostic conventional coronary angiography. *Circulation*. 2005;112: 2318–2323.
102. Raff GL, Gallagher MJ, O'Neill WW, Goldstein JA. Diagnostic accuracy of noninvasive coronary angiography using 64-slice spiral computed tomography. *J Am Coll Cardiol*. 2005;46:552–557.
103. Hausleiter J, Meyer T, Hadamitzky M, Huber E, Zankl M, Martinoff S, Kastrati A, Schömig A. Radiation dose estimates from cardiac multislice computed tomography in daily practice: impact of different scanning protocols on effective dose estimates. *Circulation*. 2006;113: 1305–1310.
104. Schmid M, Achenbach S, Ludwig J, Baum U, Anders K, Pohle K, Daniel WG, Ropers D. Visualization of coronary artery anomalies by contrast-enhanced multi-detector row spiral computed tomography. *Int J Cardiol*. 2006;111:430–435.
105. Datta J, White CS, Gilkeson RC, Meyer CA, Kansal S, Jani ML, Arildsen RC, Read K. Anomalous coronary arteries in adults: depiction at multi-detector row CT angiography. *Radiology*. 2005;235:812–818.
106. Schmitt R, Froehner S, Brunn J, Wagner M, Brunner H, Cherevatyy O, Gietzen F, Christopoulos G, Kerber S, Fellner F. Congenital anomalies of the coronary arteries: imaging with contrast-enhanced, multidetector computed tomography. *Eur Radiol*. 2005;15:1110–1121.
107. Sato Y, Inoue F, Matsumoto N, Tani S, Takayama T, Yoda S, Kunimasa T, Ishii N, Uchiyama T, Saito S, Tanaka H, Furuhashi S, Takahashi M, Koyama Y. Detection of anomalous origins of the coronary artery by means of multislice computed tomography. *Circ J*. 2005;69:320–324.
108. Shi H, Aschoff AJ, Brambs HJ, Hoffmann MH. Multislice CT imaging of anomalous coronary arteries. *Eur Radiol*. 2004;14:2172–2181.
109. van Ooijen PM, Dorgelo J, Zijlstra F, Oudkerk M. Detection, visualization and evaluation of anomalous coronary anatomy on 16-slice multidetector-row CT. *Eur Radiol*. 2004;14:2163–2171.
110. Deibler AR, Kuzo RS, Vöhringer M, Page EE, Safford RE, Patron JN, Lane GE, Morin RL, Gerber TC. Imaging of congenital coronary anomalies with multislice computed tomography. *Mayo Clin Proc*. 2004;79:1017–1023.
111. Lessick J, Kumar G, Beyar R, Lorber A, Engel A. Anomalous origin of a posterior descending artery from the right pulmonary artery: report of a rare case diagnosed by multidetector computed tomography angiography. *J Comput Assist Tomogr*. 2004;28:857–859.
112. Ropers D, Moshage W, Daniel WG, Jessl J, Gottwik M, Achenbach S. Visualization of coronary artery anomalies and their anatomic course by contrast-enhanced electron beam tomography and three-dimensional reconstruction. *Am J Cardiol*. 2001;87:193–197.
113. Ferencik M, Moselewski F, Ropers D, Hoffmann U, Baum U, Anders K, Pomerantsev EV, Abbara S, Brady TJ, Achenbach S. Quantitative parameters of image quality in multidetector spiral computed tomographic coronary imaging with submillimeter collimation. *Am J Cardiol*. 2003; 92:1257–1262.
114. Nieman K, Cademartiri F, Lemos PA, Raaijmakers R, Pattynama PM, de Feyter PJ. Reliable noninvasive coronary angiography with fast submillimeter multislice spiral computed tomography. *Circulation*. 2002;106: 2051–2054.
115. Ropers D, Baum U, Pohle K, Anders K, Ulzheimer S, Ohnesorge B, Schlundt C, Bautz W, Daniel WG, Achenbach S. Detection of coronary artery stenoses with thin-slice multi-detector row spiral computed tomography and multiplanar reconstruction. *Circulation*. 2003;107: 664–666.
116. Kuettner A, Trabold T, Schroeder S, Feyer A, Beck T, Brueckner A, Heuschmid M, Burgstahler C, Kopp AF, Claussen CD. Noninvasive detection of coronary lesions using 16-detector multislice spiral computed tomography technology: initial clinical results. *J Am Coll Cardiol*. 2004;44:1230–1237.
117. Martuscelli E, Romagnoli A, D'Eliseo A, Razzini C, Tomassini M, Sperandio M, Simonetti G, Romeo F. Accuracy of thin-slice computed tomography in the detection of coronary stenoses. *Eur Heart J*. 2004; 25:1043–1048.
118. Hoffmann U, Moselewski F, Cury RC, Ferencik M, Jang IK, Diaz LJ, Abbara S, Brady TJ, Achenbach S. Predictive value of 16-slice multidetector spiral computed tomography to detect significant obstructive coronary artery disease in patients at high risk for coronary artery disease: patient-versus segment-based analysis. *Circulation*. 2004;110: 2638–2643.
119. Fine JJ, Hopkins CB, Hall PA, Delphia RE, Attebery TW, Newton FC. Noninvasive coronary angiography: agreement of multi-slice spiral computed tomography and selective catheter angiography. *Int J Cardiovasc Imaging*. 2004;20:549–552.
120. Kaiser C, Bremerich J, Haller S, Brunner-La Rocca HP, Bongartz G, Pfisterer M, Buser P. Limited diagnostic yield of non-invasive coronary angiography by 16-slice multi-detector spiral computed tomography in routine patients referred for evaluation of coronary artery disease. *Eur Heart J*. 2005;26:1987–1992.
121. Aviram G, Finkelstein A, Herz I, Lessick J, Miller H, Graif M, Keren G. Clinical value of 16-slice multi-detector CT compared to invasive coronary angiography. *Int J Cardiovasc Intervent*. 2005;7:21–28.
122. Kuettner A, Beck T, Drosch T, Kettering K, Heuschmid M, Burgstahler C, Claussen CD, Kopp AF, Schroeder S. Diagnostic accuracy of noninvasive coronary imaging using 16-detector slice spiral computed tomography with 188 ms temporal resolution. *J Am Coll Cardiol*. 2005; 45:123–127.
123. Mollet NR, Cademartiri F, Krestin GP, McFadden EP, Arampatzis CA, Serruys PW, de Feyter PJ. Improved diagnostic accuracy with 16-row multi-slice computed tomography coronary angiography. *J Am Coll Cardiol*. 2005;45:128–132.
124. Schuijf JD, Bax JJ, Salm LP, Jukema JW, Lamb HJ, van der Wall EE, de Roos A. Noninvasive coronary imaging and assessment of left ventricular function using 16-slice computed tomography. *Am J Cardiol*. 2005;95:571–574.
125. Hoffmann MH, Shi H, Schmitz BL, Schmid FT, Lieberknecht M, Schulze R, Ludwig B, Kroschel U, Jahnke N, Haerer W, Brambs HJ, Aschoff AJ. Noninvasive coronary angiography with multislice computed tomography. *JAMA*. 2005;293:2471–2478.
126. Morgan-Hughes GJ, Roobottom CA, Owens PE, Marshall AJ. Highly accurate coronary angiography with submillimetre, 16 slice computed tomography. *Heart*. 2005;91:308–313.
127. Achenbach S, Ropers D, Pohle FK, Raaz D, von Erffa J, Yilmaz A, Muschiol G, Daniel WG. Detection of coronary artery stenoses using multi-detector CT with 16 x 0.75 collimation and 375 ms rotation. *Eur Heart J*. 2005;26:1978–1986.
128. Ehara M, Surmely JF, Kawai M, Katoh O, Matsubara T, Terashima M, Tsuchikane E, Kinoshita Y, Suzuki T, Ito T, Takeda Y, Nasu K, Tanaka N, Murata A, Suzuki Y, Sato K, Suzuki T. Diagnostic accuracy of 64-slice computed tomography for detecting angiographically significant coronary artery stenosis in an unselected consecutive patient population: comparison with conventional invasive angiography. *Circ J*. 2006;70:564–571.
129. Fine JJ, Hopkins CB, Ruff N, Newton FC. Comparison of accuracy of 64-slice cardiovascular computed tomography with coronary angiography in patients with suspected coronary artery disease. *Am J Cardiol*. 2006;97:173–174.

130. Leschka S, Alkadhi H, Plass A, Desbiolles L, Grunenfelder J, Marincek B, Wildermuth S. Accuracy of MSCT coronary angiography with 64-slice technology: first experience. *Eur Heart J*. 2005;26:1482–1487.
131. Ropers D, Rixe J, Anders K, Küttner A, Baum U, Bautz W, Daniel WG, Achenbach S. Usefulness of multidetector row spiral computed tomography with 64- x 0.6-mm collimation and 330-ms rotation for the noninvasive detection of significant coronary artery stenoses. *Am J Cardiol*. 2006;97:343–348.
132. Vanhoenacker PK, Heijenbrok-Kal MH, Van Heste R, Decramer I, Van Hoe LR, Wijns W, Hunink MG. Diagnostic performance of multidetector CT angiography for assessment of coronary artery disease: meta-analysis. *Radiology*. 2007;244:419–428.
133. Abdulla J, Abildstrom SZ, Gotzsche O, Christensen E, Kober L, Torp-Pedersen C. 64-multislice detector computed tomography coronary angiography as potential alternative to conventional coronary angiography: a systematic review and meta-analysis. *Eur Heart J*. 2007;28:3042–3050.
134. Gilard M, Cornily JC, Rioufol G, Finet G, Pennec PY, Mansourati J, Blanc JJ, Boschat J. Noninvasive assessment of left main coronary stent patency with 16-slice computed tomography. *Am J Cardiol*. 2005;95:110–112.
135. Schuijf JD, Bax JJ, Jukema JW, Lamb HJ, Warda HM, Vliegen HW, de Roos A, van der Wall EE. Feasibility of assessment of coronary stent patency using 16-slice computed tomography. *Am J Cardiol*. 2004;94:427–430.
136. Gilard M, Cornily JC, Pennec PY, Le Gal G, Nonent M, Mansourati J, Blanc JJ, Boschat J. Assessment of coronary artery stents by 16 slice computed tomography. *Heart*. 2006;92:58–61.
137. Kitagawa T, Fujii T, Tomohiro Y, Maeda K, Kobayashi M, Kunita E, Sekiguchi Y. Noninvasive assessment of coronary stents in patients by 16-slice computed tomography. *Int J Cardiol*. 2006;109:188–194.
138. Gaspar T, Halon DA, Lewis BS, Adawi S, Schliamser JE, Rubinshtein R, Flugelman MY, Peled N. Diagnosis of coronary in-stent restenosis with multidetector row spiral computed tomography. *J Am Coll Cardiol*. 2005;46:1573–1579.
139. Cademartiri F, Mollet N, Lemos PA, Pugliese F, Baks T, McFadden EP, Krestin GP, de Feyter PJ. Usefulness of multislice computed tomographic coronary angiography to assess in-stent restenosis. *Am J Cardiol*. 2005;96:799–802.
140. Rixe J, Achenbach S, Ropers D, Baum U, Kuettner A, Ropers U, Bautz W, Daniel WG, Anders K. Assessment of coronary artery stent restenosis by 64-slice multi-detector computed tomography. *Eur Heart J*. 2006;27:2567–2572.
141. Hong C, Chrysant GS, Woodard PK, Bae KT. Coronary artery stent patency assessed with in-stent contrast enhancement measured at multidetector row CT angiography: initial experience. *Radiology*. 2004;233:286–291.
142. Mahnken AH, Buecker A, Wildberger JE, Ruebben A, Stanzel S, Vogt F, Günther RW, Blindt R. Coronary artery stents in multislice computed tomography: in vitro artifact evaluation. *Invest Radiol*. 2004;39:27–33.
143. Maintz D, Seifarth H, Flohr T, Krämer S, Wichter T, Heindel W, Fischbach R. Improved coronary artery stent visualization and in-stent stenosis detection using 16-slice computed-tomography and dedicated image reconstruction technique. *Invest Radiol*. 2003;38:790–795.
144. Seifarth H, Raupach R, Schaller S, Fallenberg EM, Flohr T, Heindel W, Fischbach R, Maintz D. Assessment of coronary artery stents using 16-slice MDCT angiography: evaluation of a dedicated reconstruction kernel and a noise reduction filter. *Eur Radiol*. 2005;15:721–726.
145. Martuscelli E, Romagnoli A, D'Eliseo A, Tomassini M, Razzini C, Sperandio M, Simonetti G, Romeo F, Mehta JL. Evaluation of venous and arterial conduit patency by 16-slice spiral computed tomography. *Circulation*. 2004;110:3234–3238.
146. Nieman K, Pattynama PM, Rensing BJ, Van Geuns RJ, De Feyter PJ. Evaluation of patients after coronary artery bypass surgery: CT angiographic assessment of grafts and coronary arteries. *Radiology*. 2003;229:749–756.
147. Schlosser T, Konorza T, Hunold P, Kühl H, Schmermund A, Barkhausen J. Noninvasive visualization of coronary artery bypass grafts using 16-detector row computed tomography. *J Am Coll Cardiol*. 2004;44:1224–1229.
148. Anders K, Baum U, Schmid M, Ropers D, Schmid A, Pohle K, Daniel WG, Bautz W, Achenbach S. Coronary artery bypass graft (CABG) patency: assessment with high-resolution submillimeter 16-slice multidetector-row computed tomography (MDCT) versus coronary angiography. *Eur J Radiol*. 2006;57:336–344.
149. Burgstahler C, Beck T, Kuettner A, Drosch T, Kopp AF, Heuschmid M, Claussen CD, Schroeder S. Non-invasive evaluation of coronary artery bypass grafts using 16-row multi-slice computed tomography with 188 ms temporal resolution. *Int J Cardiol*. 2006;106:244–249.
150. Chiurlia E, Menozzi M, Ratti C, Romagnoli R, Modena MG. Follow-up of coronary artery bypass graft patency by multislice computed tomography. *Am J Cardiol*. 2005;95:1094–1097.
151. Moore RK, Sampson C, MacDonald S, Moynahan C, Groves D, Chester MR. Coronary artery bypass graft imaging using ECG-gated multislice computed tomography: comparison with catheter angiography. *Clin Radiol*. 2005;60:990–998.
152. Pache G, Saueressig U, Frydrychowicz A, Foell D, Ghanem N, Kotter E, Geibel-Zehender A, Bode C, Langer M, Bley T. Initial experience with 64-slice cardiac CT: non-invasive visualization of coronary artery bypass grafts. *Eur Heart J*. 2006;27:976–980.
153. Salm LP, Bax JJ, Jukema JW, Schuijf JD, Vliegen HW, Lamb HJ, van der Wall EE, de Roos A. Comprehensive assessment of patients after coronary artery bypass grafting by 16-detector-row computed tomography. *Am Heart J*. 2005;150:775–781.
154. Malagutti P, Nieman K, Meijboom WB, van Mieghem CA, Pugliese F, Cademartiri F, Mollet NR, Boersma E, de Jaegere PP, de Feyter PJ. Use of 64-slice CT in symptomatic patients after coronary bypass surgery: evaluation of grafts and coronary arteries. *Eur Heart J*. 2007;28:1879–1885.
155. Nickoloff EL, Alderson PO. Radiation exposures to patients from CT: reality, public perception, and policy. *AJR Am J Roentgenol*. 2001;177:285–287.
156. Delaney A, Carter A, Fisher M. The prevention of anaphylactoid reactions to iodinated radiological contrast media: a systematic review. *BMC Med Imaging*. 2006;6:2.
157. Masui T, Katayama M, Kobayashi S, Sakahara H. Intravenous injection of high and medium concentrations of computed tomography contrast media and related heat sensation, local pain, and adverse reactions. *J Comput Assist Tomogr*. 2005;29:704–708.
158. Cochran ST. Anaphylactoid reactions to radiocontrast media. *Curr Allergy Asthma Rep*. 2005;5:28–31.
159. Laroche D, Vergnaud MC, Lefrancois C, Hue S, Bricard H. Anaphylactoid reactions to iodinated contrast media. *Acad Radiol*. 2002;9(suppl 2):S431–S432.
160. Morcos SK, Thomsen HS. Adverse reactions to iodinated contrast media. *Eur Radiol*. 2001;11:1267–1275.
161. Spring DB, Bettmann MA, Barkan HE. Nonfatal adverse reactions to iodinated contrast media: spontaneous reporting to the U.S. Food and Drug Administration, 1978–1994. *Radiology*. 1997;204:325–332.
162. Brenner D, Elliston C, Hall E, Berdon W. Estimated risks of radiation-induced fatal cancer from pediatric CT. *AJR Am J Roentgenol*. 2001;176:289–296.
163. Garcia-Peña P, Lucaya J. HRCT in children: technique and indications. *Eur Radiol*. 2004;14(suppl 4):L13–L30.
164. Fayad ZA. MR imaging for the noninvasive assessment of atherothrombotic plaques. *Magn Reson Imaging Clin N Am*. 2003;11:101–113.
165. Flamm SD, Muthupillai R. Coronary artery magnetic resonance angiography. *J Magn Reson Imaging*. 2004;19:686–709.
166. Flohr T, Stierstorfer K, Raupach R, Ulzheimer S, Bruder H. Performance evaluation of a 64-slice CT system with z-flying focal spot. *Rofo*. 2004;176:1803–1810.
167. Gerber TC, Kuzo RS, Karstaedt N, Lane GE, Morin RL, Sheedy PF 2nd, Safford RE, Blackshear JL, Pietan JH. Current results and new developments of coronary angiography with use of contrast-enhanced computed tomography of the heart. *Mayo Clin Proc*. 2002;77:55–71.
168. Lu B, Dai R, Bai H, He S, Jing B, Zhuang N, Gao R, Yang Y, Chen J, Budoff MJ. Evaluation of electron beam tomographic coronary arteriography with three-dimensional reconstruction in healthy subjects. *Angiology*. 2000;51:895–904.
169. Austen WG, Edwards JE, Frye RL, Gensini GG, Gott VL, Griffith LS, McGoon DC, Murphy ML, Roe BB. A reporting system on patients evaluated for coronary artery disease. Report of the Ad Hoc Committee for Grading of Coronary Artery Disease, Council on Cardiovascular Surgery, American Heart Association. *Circulation*. 1975;51(suppl 4):5–40.
170. Mahnken AH, Katoh M, Bruners P, Spuentrup E, Wildberger JE, Gunther RW, Buecker A. Acute myocardial infarction: assessment of left ventricular function with 16-detector row spiral CT versus MR imaging: study in pigs. *Radiology*. 2005;236:112–117.

171. Falk E, Shah PK, Fuster V. Coronary plaque disruption. *Circulation*. 1995;92:657–671.
172. Little WC, Constantinescu M, Applegate RJ, Kutcher MA, Burrows MT, Kahl FR, Santamore WP. Can coronary angiography predict the site of a subsequent myocardial infarction in patients with mild-to-moderate coronary artery disease? *Circulation*. 1988;78:1157–1166.
173. Naghavi M, Libby P, Falk E, Casscells SW, Litovsky S, Rumberger J, Badimon JJ, Stefanadis C, Moreno P, Pasterkamp G, Fayad Z, Stone PH, Waxman S, Raggi P, Madjid M, Zarrabi A, Burke A, Yuan C, Fitzgerald PJ, Siscovick DS, de Korte CL, Aikawa M, Airaksinen KE, Assmann G, Becker CR, Chesebro JH, Farb A, Galis ZS, Jackson C, Jang IK, Koenig W, Lodder RA, March K, Demirovic J, Navab M, Priori SG, Rekhter MD, Bahr R, Grundy SM, Mehran R, Colombo A, Boerwinkle E, Ballantyne C, Insull W Jr, Schwartz RS, Vogel R, Serruys PW, Hansson GK, Faxon DP, Kaul S, Drexler H, Greenland P, Muller JE, Virmani R, Ridker PM, Zipes DP, Shah PK, Willerson JT. From vulnerable plaque to vulnerable patient: a call for new definitions and risk assessment strategies: part I. *Circulation*. 2003;108:1664–1672.
174. Stary HC, Chandler AB, Dinsmore RE, Fuster V, Glagov S, Insull W Jr, Rosenfeld ME, Schwartz CJ, Wagner WD, Wissler RW. A definition of advanced types of atherosclerotic lesions and a histological classification of atherosclerosis. A report from the Committee on Vascular Lesions of the Council on Arteriosclerosis, American Heart Association. *Circulation*. 1995;92:1355–1374.
175. Rasouli ML. CT imaging of non-calcific atherosclerotic plaque with cardiac computed tomography. In: Budoff MJ, Shinbane JS, eds. *Cardiac CT Imaging: Diagnosis of Cardiovascular Disease.* London: Springer; 2006:165–172.
176. Budoff MJ. Prevalence of soft plaque detection with computed tomography. *J Am Coll Cardiol*. 2006;48:319–321.
177. Achenbach S, Moselewski F, Ropers D, Ferencik M, Hoffmann U, MacNeill B, Pohle K, Baum U, Anders K, Jang IK, Daniel WG, Brady TJ. Detection of calcified and noncalcified coronary atherosclerotic plaque by contrast-enhanced, submillimeter multidetector spiral computed tomography: a segment-based comparison with intravascular ultrasound. *Circulation*. 2004;109:14–17.
178. Kim WY, Stuber M, Börnert P, Kissinger KV, Manning WJ, Botnar RM. Three-dimensional black-blood cardiac magnetic resonance coronary vessel wall imaging detects positive arterial remodeling in patients with nonsignificant coronary artery disease. *Circulation*. 2002; 106:296–299.
179. Leber AW, Becker A, Knez A, von Ziegler F, Sirol M, Nikolaou K, Ohnesorge B, Fayad ZA, Becker CR, Reiser M, Steinbeck G, Boekstegers P. Accuracy of 64-slice computed tomography to classify and quantify plaque volumes in the proximal coronary system: a comparative study using intravascular ultrasound. *J Am Coll Cardiol*. 2006; 47:672–677.
180. Baumgart D, Schmermund A, Goerge G, Haude M, Ge J, Adamzik M, Sehnert C, Altmaier K, Groenemeyer D, Seibel R, Erbel R. Comparison of electron beam computed tomography with intracoronary ultrasound and coronary angiography for detection of coronary atherosclerosis. *J Am Coll Cardiol*. 1997;30:57–64.
181. Leber AW, Knez A, Becker A, Becker C, von Ziegler F, Nikolaou K, Rist C, Reiser M, White C, Steinbeck G, Boekstegers P. Accuracy of multidetector spiral computed tomography in identifying and differentiating the composition of coronary atherosclerotic plaques: a comparative study with intracoronary ultrasound. *J Am Coll Cardiol*. 2004; 43:1241–1247.
182. Rasouli MLSD, McKay C, French WJ, Budoff MJ. Electron beam angiography in the assessment of coronary plaque morphology. *Catheter Cardiovasc Interv*. 2004;62:A3.
183. Schoenhagen P, Tuzcu EM, Stillman AE, Moliterno DJ, Halliburton SS, Kuzmiak SA, Kasper JM, Magyar WA, Lieber ML, Nissen SE, White RD. Non-invasive assessment of plaque morphology and remodeling in mildly stenotic coronary segments: comparison of 16-slice computed tomography and intravascular ultrasound. *Coron Artery Dis*. 2003;14: 459–462.
184. Schroeder S, Kopp AF, Baumbach A, Meisner C, Kuettner A, Georg C, Ohnesorge B, Herdeg C, Claussen CD, Karsch KR. Noninvasive detection and evaluation of atherosclerotic coronary plaques with multislice computed tomography. *J Am Coll Cardiol*. 2001;37:1430–1435.
185. Moselewski F, Ropers D, Pohle K, Hoffmann U, Ferencik M, Chan RC, Cury RC, Abbara S, Jang IK, Brady TJ, Daniel WG, Achenbach S. Comparison of measurement of cross-sectional coronary atherosclerotic plaque and vessel areas by 16-slice multidetector computed tomography versus intravascular ultrasound. *Am J Cardiol*. 2004;94:1294–1297.
186. Budoff MJ, Achenbach S, Blumenthal RS, Carr JJ, Goldin JG, Greenland P, Guerci AD, Lima JA, Rader DJ, Rubin GD, Shaw LJ, Wiegers SE. Assessment of coronary artery disease by cardiac computed tomography: a scientific statement from the American Heart Association Committee on Cardiovascular Imaging and Intervention, Council on Cardiovascular Radiology and Intervention, and Committee on Cardiac Imaging, Council on Clinical Cardiology. *Circulation*. 2006;114: 1761–1791.
187. Botnar RM, Kim WY, Börnert P, Stuber M, Spuentrup E, Manning WJ. 3D coronary vessel wall imaging utilizing a local inversion technique with spiral image acquisition. *Magn Reson Med*. 2001;46:848–854.
188. von Ingersleben G, Schmiedl UP, Hatsukami TS, Nelson JA, Subramaniam DS, Ferguson MS, Yuan C. Characterization of atherosclerotic plaques at the carotid bifurcation: correlation of high-resolution MR imaging with histologic analysis: preliminary study. *Radiographics*. 1997;17:1417–1423.
189. Fayad ZA, Nahar T, Fallon JT, Goldman M, Aguinaldo JG, Badimon JJ, Shinnar M, Chesebro JH, Fuster V. In vivo magnetic resonance evaluation of atherosclerotic plaques in the human thoracic aorta: a comparison with transesophageal echocardiography. *Circulation*. 2000;101: 2503–2509.
190. Edelman RR, Mattle HP, Wallner B, Bajakian R, Kleefield J, Kent C, Skillman JJ, Mendel JB, Atkinson DJ. Extracranial carotid arteries: evaluation with "black blood" MR angiography. *Radiology*. 1990;177: 45–50.
191. Shunk KA, Garot J, Atalar E, Lima JA. Transesophageal magnetic resonance imaging of the aortic arch and descending thoracic aorta in patients with aortic atherosclerosis. *J Am Coll Cardiol*. 2001;37: 2031–2035.
192. Hatsukami TS, Ross R, Polissar NL, Yuan C. Visualization of fibrous cap thickness and rupture in human atherosclerotic carotid plaque in vivo with high-resolution magnetic resonance imaging. *Circulation*. 2000;102:959–964.
193. Chan SK, Jaffer FA, Botnar RM, Kissinger KV, Goepfert L, Chuang ML, O'Donnell CJ, Levy D, Manning WJ. Scan reproducibility of magnetic resonance imaging assessment of aortic atherosclerosis burden. *J Cardiovasc Magn Reson*. 2001;3:331–338.
194. Yuan C, Mitsumori LM, Ferguson MS, Polissar NL, Echelard D, Ortiz G, Small R, Davies JW, Kerwin WS, Hatsukami TS. In vivo accuracy of multispectral magnetic resonance imaging for identifying lipid-rich necrotic cores and intraplaque hemorrhage in advanced human carotid plaques. *Circulation*. 2001;104:2051–2056.
195. Kramer CM. Magnetic resonance imaging to identify the high-risk plaque. *Am J Cardiol*. 2002;90:15L–17L.
196. Yuan C, Beach KW, Smith LH Jr, Hatsukami TS. Measurement of atherosclerotic carotid plaque size in vivo using high resolution magnetic resonance imaging. *Circulation*. 1998;98:2666–2671.
197. Luo Y, Polissar N, Han C, Yarnykh V, Kerwin WS, Hatsukami TS, Yuan C. Accuracy and uniqueness of three in vivo measurements of atherosclerotic carotid plaque morphology with black blood MRI. *Magn Reson Med*. 2003;50:75–82.
198. Newman AB, Naydeck B, Sutton-Tyrrell K, Edmundowicz D, Gottdiener J, Kuller LH. Coronary artery calcification in older adults with minimal clinical or subclinical cardiovascular disease. *J Am Geriatr Soc*. 2000;48:256–263.
199. Toussaint JF, Southern JF, Fuster V, Kantor HL. T2-weighted contrast for NMR characterization of human atherosclerosis. *Arterioscler Thromb Vasc Biol*. 1995;15:1533–1542.
200. Li D, Dolan RP, Walovitch RC, Lauffer RB. Three-dimensional MRI of coronary arteries using an intravascular contrast agent. *Magn Reson Med*. 1998;39:1014–1018.
201. Stillman AE, Wilke N, Jerosch-Herold M. Use of an intravascular T1 contrast agent to improve MR cine myocardial-blood pool definition in man. *J Magn Reson Imaging*. 1997;7:765–767.
202. Taylor AM, Panting JR, Keegan J, Gatehouse PD, Amin D, Jhooti P, Yang GZ, McGill S, Burman ED, Francis JM, Firmin DN, Pennell DJ. Safety and preliminary findings with the intravascular contrast agent NC100150 injection for MR coronary angiography. *J Magn Reson Imaging*. 1999;9:220–227.
203. Huber ME, Paetsch I, Schnackenburg B, Bornstedt A, Nagel E, Fleck E, Boesiger P, Maggioni F, Cavagna FM, Stuber M. Performance of a new gadolinium-based intravascular contrast agent in free-breathing

inversion-recovery 3D coronary MRA. *Magn Reson Med*. 2003;49:115–121.
204. Kim WY, Stuber M, Kissinger KV, Andersen NT, Manning WJ, Botnar RM. Impact of bulk cardiac motion on right coronary MR angiography and vessel wall imaging. *J Magn Reson Imaging*. 2001;14:383–390.
205. Herborn CU, Barkhausen J, Paetsch I, Hunold P, Mahler M, Shamsi K, Nagel E. Coronary arteries: contrast-enhanced MR imaging with SH L 643A: experience in 12 volunteers. *Radiology*. 2003;229:217–223.
206. Manning WJ, Li W, Edelman RR. A preliminary report comparing magnetic resonance coronary angiography with conventional angiography. *N Engl J Med*. 1993;328:828–832.
207. Pennell DJ, Bogren HG, Keegan J, Firmin DN, Underwood SR. Assessment of coronary artery stenosis by magnetic resonance imaging. *Heart*. 1996;75:127–133.
208. Post JC, van Rossum AC, Hofman MB, de Cock CC, Valk J, Visser CA. Clinical utility of two-dimensional magnetic resonance angiography in detecting coronary artery disease. *Eur Heart J*. 1997;18:426–433.
209. Woodard PK, Li D, Haacke EM, Dhawale PJ, Kaushikkar S, Barzilai B, Braverman AC, Ludbrook PA, Weiss AN, Brown JJ, Mirowitz SA, Pilgram TK, Gutierrez FR. Detection of coronary stenoses on source and projection images using three-dimensional MR angiography with retrospective respiratory gating: preliminary experience. *AJR Am J Roentgenol*. 1998;170:883–888.
210. Kessler W, Achenbach S, Moshage W, Zink D, Kroeker R, Nitz W, Laub G, Bachmann K. Usefulness of respiratory gated magnetic resonance coronary angiography in assessing narrowings > or = 50% in diameter in native coronary arteries and in aortocoronary bypass conduits. *Am J Cardiol*. 1997;80:989–993.
211. Sandstede JJ, Pabst T, Beer M, Geis N, Kenn W, Neubauer S, Hahn D. Three-dimensional MR coronary angiography using the navigator technique compared with conventional coronary angiography. *AJR Am J Roentgenol*. 1999;172:135–139.
212. van Geuns RJ, de Bruin HG, Rensing BJ, Wielopolski PA, Hulshoff MD, van Ooijen PM, Oudkerk M, de Feyter PJ. Magnetic resonance imaging of the coronary arteries: clinical results from three dimensional evaluation of a respiratory gated technique. *Heart*. 1999;82:515–519.
213. Huber A, Nikolaou K, Gonschior P, Knez A, Stehling M, Reiser M. Navigator echo-based respiratory gating for three-dimensional MR coronary angiography: results from healthy volunteers and patients with proximal coronary artery stenoses. *AJR Am J Roentgenol*. 1999;173:95–101.
214. Sardanelli F, Molinari G, Zandrino F, Balbi M. Three-dimensional, navigator-echo MR coronary angiography in detecting stenoses of the major epicardial vessels, with conventional coronary angiography as the standard of reference. *Radiology*. 2000;214:808–814.
215. Wittlinger T, Voigtländer T, Rohr M, Meyer J, Thelen M, Kreitner KF, Kalden P. Magnetic resonance imaging of coronary artery occlusions in the navigator technique. *Int J Cardiovasc Imaging*. 18:203–215.
216. Kim WY, Danias PG, Stuber M, Flamm SD, Plein S, Nagel E, Langerak SE, Weber OM, Pedersen EM, Schmidt M, Botnar RM, Manning WJ. Coronary magnetic resonance angiography for the detection of coronary stenoses. *N Engl J Med*. 2001;345:1863–1869.
217. Weber C, Steiner P, Sinkus R, Dill T, Börnert P, Adam G. Correlation of 3D MR coronary angiography with selective coronary angiography: feasibility of the motion-adapted gating technique. *Eur Radiol*. 2002;12:718–726.
218. Jahnke C, Paetsch I, Nehrke K, Schnackenburg B, Gebker R, Fleck E, Nagel E. Rapid and complete coronary arterial tree visualization with magnetic resonance imaging: feasibility and diagnostic performance. *Eur Heart J*. 2005;26:2313–2319.
219. Regenfus M, Ropers D, Achenbach S, Kessler W, Laub G, Daniel WG, Moshage W. Noninvasive detection of coronary artery stenosis using contrast-enhanced three-dimensional breath-hold magnetic resonance coronary angiography. *J Am Coll Cardiol*. 2000;36:44–50.
220. Rubinstein RI, Askenase AD, Thickman D, Feldman MS, Agarwal JB, Helfant RH. Magnetic resonance imaging to evaluate patency of aortocoronary bypass grafts. *Circulation*. 1987;76:786–791.
221. Jenkins JP, Love HG, Foster CJ, Isherwood I, Rowlands DJ. Detection of coronary artery bypass graft patency as assessed by magnetic resonance imaging. *Br J Radiol*. 1988;61:2–4.
222. Garcia MJ, Lessick J, Hoffmann MH, CATSCAN Study Investigators. Accuracy of 16-row multidetector computed tomography for the assessment of coronary artery stenosis. *JAMA*. 2006;296:403–411.
223. Cordeiro MA, Miller JM, Schmidt A, Lardo AC, Rosen BD, Bush DE, Brinker JA, Bluemke DA, Shapiro EP, Lima JA. Non-invasive half millimetre 32 detector row computed tomography angiography accurately excludes significant stenoses in patients with advanced coronary artery disease and high calcium scores. *Heart*. 2006;92:589–597.
224. Nikolaou K, Knez A, Rist C, Wintersperger BJ, Leber A, Johnson T, Reiser MF, Becker CR. Accuracy of 64-MDCT in the diagnosis of ischemic heart disease. *AJR Am J Roentgenol*. 2006;187:111–117.
225. Schlosser T, Mohrs OK, Magedanz A, Nowak B, Voigtländer T, Barkhausen J, Schmermund A. Noninvasive coronary angiography using 64-detector-row computed tomography in patients with a low to moderate pretest probability of significant coronary artery disease. *Acta Radiol*. 2007;48:300–307.
226. Muhlenbruch G, Seyfarth T, Soo CS, Pregalathan N, Mahnken AH. Diagnostic value of 64-slice multi-detector row cardiac CTA in symptomatic patients. *Eur Radiol*. 2007;17:603–609.
227. Meijboom WB, Mollet NR, Van Mieghem CA, Weustink AC, Pugliese F, van Pelt N, Cademartiri F, Vourvouri E, de Jaegere P, Krestin GP, de Feyter PJ. 64-Slice CT coronary angiography in patients with non-ST elevation acute coronary syndrome. *Heart*. 2007;93:1386–1392.
228. Schuijf JD, Pundziute G, Jukema JW, Lamb HJ, van der Hoeven BL, de Roos A, van der Wall EE, Bax JJ. Diagnostic accuracy of 64-slice multislice computed tomography in the noninvasive evaluation of significant coronary artery disease. *Am J Cardiol*. 2006;98:145–148.
229. Oncel D, Oncel G, Tastan A, Tamci B. Detection of significant coronary artery stenosis with 64-section MDCT angiography. *Eur J Radiol*. 2007;62:394–405.
230. Herzog C, Zwerner PL, Doll JR, Nielsen CD, Nguyen SA, Savino G, Vogl TJ, Costello P, Schoepf UJ. Significant coronary artery stenosis: comparison on per-patient and per-vessel or per-segment basis at 64-section CT angiography. *Radiology*. 2007;244:112–120.
231. Ehara M, Kawai M, Surmely JF, Matsubara T, Terashima M, Tsuchikane E, Kinoshita Y, Ito T, Takeda Y, Nasu K, Tanaka N, Murata A, Fujita H, Sato K, Kodama A, Katoh O, Suzuki T. Diagnostic accuracy of coronary in-stent restenosis using 64-slice computed tomography: comparison with invasive coronary angiography. *J Am Coll Cardiol*. 2007;49:951–959.
232. Shabestari AA, Abdi S, Akhlaghpoor S, Azadi M, Baharjoo H, Pajouh MD, Emami Z, Esfahani F, Firouzi I, Hashemian M, Kouhi M, Mozafari M, Nazeri I, Rohshani M, Salevatipour B, Tavalla H, Tehrai M, Zarrabi A. Diagnostic performance of 64-channel multislice computed tomography in assessment of significant coronary artery disease in symptomatic subjects. *Am J Cardiol*. 2007;99:1656–1661.
233. Cademartiri F, Maffei E, Palumbo A, Malagò R, Alberghina F, Aldrovandi A, Brambilla V, Runza G, La Grutta L, Menozzi A, Vignali L, Casolo G, Midiri M, Mollet NR. Diagnostic accuracy of 64-slice computed tomography coronary angiography in patients with low-to-intermediate risk. *Radiol Med (Torino)*. 2007;112:969–981.
234. Hausleiter J, Meyer T, Hadamitzky M, Zankl M, Gerein P, Dörrler K, Kastrati A, Martinoff S, Schömig A. Non-invasive coronary computed tomographic angiography for patients with suspected coronary artery disease: the Coronary Angiography by Computed Tomography with the Use of a Submillimeter resolution (CACTUS) trial. *Eur Heart J*. 2007;28:3034–3041.
235. Meijboom WB, van Mieghem CA, Mollet NR, Pugliese F, Weustink AC, van Pelt N, Cademartiri F, Nieman K, Boersma E, de Jaegere P, Krestin GP, de Feyter PJ. 64-Slice computed tomography coronary angiography in patients with high, intermediate, or low pretest probability of significant coronary artery disease. *J Am Coll Cardiol*. 2007;50:1469–1475.
236. Andreini D, Pontone G, Pepi M, Ballerini G, Bartorelli AL, Magini A, Quaglia C, Nobili E, Agostoni P. Diagnostic accuracy of multidetector computed tomography coronary angiography in patients with dilated cardiomyopathy. *J Am Coll Cardiol*. 2007;49:2044–2050.
237. Pundziute G, Schuijf JD, Jukema JW, van Werkhoven JM, Boersma E, de Roos A, van der Wall EE, Bax JJ. Gender influence on the diagnostic accuracy of 64-slice multislice computed tomography coronary angiography for detection of obstructive coronary artery disease. *Heart*. 2008;94:48–52.
238. Weustink AC, Meijboom WB, Mollet NR, Otsuka M, Pugliese F, van Mieghem C, Malago R, van Pelt N, Dijkshoorn ML, Cademartiri F, Krestin GP, de Feyter PJ. Reliable high-speed coronary computed tomography in symptomatic patients. *J Am Coll Cardiol*. 2007;50:786–794.
239. Leber AW, Johnson T, Becker A, von Ziegler F, Tittus J, Nikolaou K, Reiser M, Steinbeck G, Becker CR, Knez A. Diagnostic accuracy of dual-source multi-slice CT-coronary angiography in patients with an

intermediate pretest likelihood for coronary artery disease. *Eur Heart J*. 2007;28:2354–2360.
240. Scheffel H, Alkadhi H, Plass A, Vachenauer R, Desbiolles L, Gaemperli O, Schepis T, Frauenfelder T, Schertler T, Husmann L, Grunenfelder J, Genoni M, Kaufmann PA, Marincek B, Leschka S. Accuracy of dual-source CT coronary angiography: first experience in a high pre-test probability population without heart rate control. *Eur Radiol*. 2006;16:2739–2747.
241. Oncel D, Oncel G, Tastan A. Effectiveness of dual-source CT coronary angiography for the evaluation of coronary artery disease in patients with atrial fibrillation: initial experience. *Radiology*. 2007;245:703–711.
242. Johnson TR, Nikolaou K, Busch S, Leber AW, Becker A, Wintersperger BJ, Rist C, Knez A, Reiser MF, Becker CR. Diagnostic accuracy of dual-source computed tomography in the diagnosis of coronary artery disease. *Invest Radiol*. 2007;42:684–691.
243. Ropers U, Ropers D, Pflederer T, Anders K, Kuettner A, Stilianakis NI, Komatsu S, Kalender W, Bautz W, Daniel WG, Achenbach S. Influence of heart rate on the diagnostic accuracy of dual-source computed tomography coronary angiography. *J Am Coll Cardiol*. 2007;50:2393–2398.
244. Heuschmid M, Burgstahler C, Reimann A, Brodoefel H, Mysal I, Haeberle E, Tsiflikas I, Claussen CD, Kopp AF, Schroeder S. Usefulness of noninvasive cardiac imaging using dual-source computed tomography in an unselected population with high prevalence of coronary artery disease. *Am J Cardiol*. 2007;100:587–592.
245. Meyer TS, Martinoff S, Hadamitzky M, Will A, Kastrati A, Schömig A, Hausleiter J. Improved noninvasive assessment of coronary artery bypass grafts with 64-slice computed tomographic angiography in an unselected patient population. *J Am Coll Cardiol*. 2007;49:946–950.
246. Onuma Y, Tanabe K, Chihara R, Yamamoto H, Miura Y, Kigawa I, Fukuda S, Miyairi T, Nakajima H, Hara K. Evaluation of coronary artery bypass grafts and native coronary arteries using 64-slice multidetector computed tomography. *Am Heart J*. 2007;154:519–526.
247. Feuchtner GM, Schachner T, Bonatti J, Friedrich GJ, Soegner P, Klauser A, zur Nedden D. Diagnostic performance of 64-slice computed tomography in evaluation of coronary artery bypass grafts. *AJR Am J Roentgenol*. 2007;189:574–580.
248. Ropers D, Pohle FK, Kuettner A, Pflederer T, Anders K, Daniel WG, Bautz W, Baum U, Achenbach S. Diagnostic accuracy of noninvasive coronary angiography in patients after bypass surgery using 64-slice spiral computed tomography with 330-ms gantry rotation. *Circulation*. 2006;114:2334–2341.

KEY WORDS: AHA Scientific Statements ■ angiography ■ imaging

Noninvasive Coronary Artery Imaging. Magnetic Resonance Angiography and Multidetector Computed Tomography Angiography. A Scientific Statement From the American Heart Association Committee on Cardiovascular Imaging and Intervention of the Council on Cardiovascular Radiology and Intervention, and the Councils on Clinical Cardiology and Cardiovascular Disease in the Young

David A. Bluemke, Stephan Achenbach, Matthew Budoff, Thomas C. Gerber, Bernard Gersh, L. David Hillis, W. Gregory Hundley, Warren J. Manning, Beth Feller Printz, Matthias Stuber and Pamela K. Woodard

Circulation. published online June 27, 2008;
Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231

Print ISSN: 0009-7322. Online ISSN: 1524-4539