Noninvasive Coronary Imaging in the New Millennium: A Comparison of Computed Tomography and Magnetic Resonance Techniques

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Until recently, visualization of the coronary arteries was the sole domain of catheter-based x-ray angiography. In an effort to detect and assess coronary artery disease noninvasively, magnetic resonance imaging, electron beam computed tomography, and multislice spiral computed tomography have emerged as potential modalities. Besides visualization of the vessel lumen, these techniques may be capable of imaging and characterizing atherosclerotic plaques. None of these techniques are yet routinely used, but considering the pace of the technical advancements, clinically reliable noninvasive coronary angiography can be expected in the coming years.
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Conventional x-ray coronary angiography with selective intracoronary injection of contrast medium remains the undisputed standard of reference for the luminal assessment of the coronary arteries. Additionally, intracoronary ultrasound, Doppler, pressure measurements, and numerous other applications under development further visualize the coronary wall and quantify the hemodynamic consequences of obstructive coronary artery disease.

However, cardiac catheterization and selective coronary angiography are invasive procedures that yield a small but not negligible health risk and cause patient discomfort. So despite the diagnostic superiority of the procedure, substantial effort has been invested in the development of noninvasive techniques for visualization of the coronary arteries. Several modalities, such as electron beam computed tomography (EBCT), magnetic resonance imaging (MRI) and most recently multislice spiral computed tomography (MSCT) have been investigated. The scan characteristics and some of the clinical experience with these techniques will be discussed.

Substantial effort has been invested in the development of noninvasive techniques for visualization of the coronary arteries.

Noninvasive Assessment of the Coronary Lumen

Imaging of the coronary arteries is not an easy task. The small and tortuous epicardial vessels follow multiple nonlinear courses around the heart and are in constant motion. Besides displacement due to cardiac contraction, the coronary arteries are also displaced by respiration. To visualize the coronary lumen, its characteristics need to be altered in such a way that it can be sufficiently discriminated from the vessel wall and surrounding tissues.

For the purpose of stenosis quantification in vessels with a diameter as small as 2 mm, the spatial resolution would have to be around 0.2 mm in all three dimensions. To differentiate plaque components, it may need to be better still. The acquisition or reconstruction of images needs to be synchronized to the cardiac cycle and to the respiration. Although the coronary arteries are never completely immobile, motion is limited during the mid-to-end diastolic phase. For coronary visualization, the data acquisition or image reconstruction should be limited to this short period of relative immobility. Besides consistent electrocardiogram (ECG) synchronization, the scan or reconstruction window needs to be as short as possible to reduce the chance of motion artifacts. For complete coronary assessment, the entire coronary artery system needs to be covered within a practically feasible examination time. In the case of the computed tomography (CT) modalities, the entire heart needs to be covered within the time of a single breath-hold to avoid multiple contrast injections. Ideally, a noninvasive technique should not be harmful and should be accessible to all patients.

Magnetic Resonance Imaging

MRI is a tomographic imaging technique based on the magnetic characteristics of tissues and molecules within a magnetic field. Advancements in scanner technology and also microprocessor technology have increased the quantitative and qualitative performance of MRI. Considerable volumes can be scanned during a single breath-hold, and even real-time MR imaging has become a reality. An ever-expanding arsenal of morphologic and functional applications is being developed. MRI is the most attractive modality with respect to the patient's health.

The small and tortuous epicardial vessels follow multiple nonlinear courses around the heart.

The currently used MRI systems and scan protocols do not pose health hazards, and the use of contrast agents is optional.

The first publications related to clinical MR coronary angiography date from the early 1990s, and the

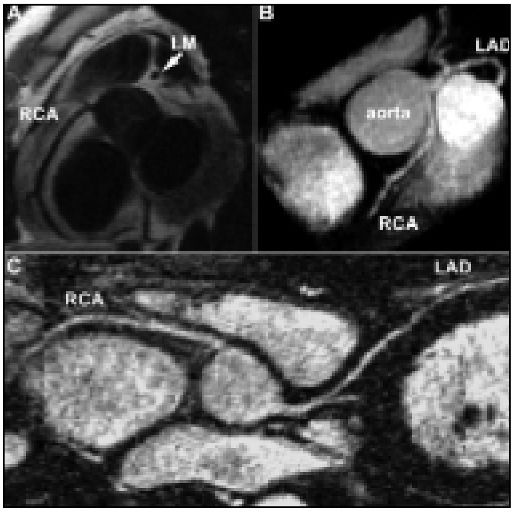


Figure 1. *Magnetic resonance coronary angiography.* **(A)** *Two-dimensional, high-resolution, black-blood image of the right coronary artery (RCA) and cross-section of the left main coronary artery (LM).* **(B)** *Three-dimensional volume acquired during a single breath-hold of the aortic root showing an aberrant course of the RCA from the left coronary sinus between the aorta and pulmonary trunk.* **(C)** *Multislice true FISP (fast imaging with steadystate precession) acquisition, showing both the RCA and left anterior descending coronary artery (LAD) in a curved multiplanar reconstruction.*

Table 1
Modality Characteristics of Noninvasive Angiography

	Magnetic Resonance Imaging	Electron Beam Computed Tomography	Multislice Spiral Computed Tomography
Data acquisition	Various (2D/3D)	Sequential	Continuous spiral
Respiratory motion	Breath hold or respiratory gated	Breath hold	Breath hold
ECG synchronization	Prospective trigger	Prospective trigger	Retrospective gating
HR optimization		β-blocker (HR↓)	Atropine (HR↑)
Temporal resolution (ms)	70–200	100	≤250
Coverage (cm)	Various	≤ Entire heart	Entire heart
Scan protocol (mm)	Various	1 × 3 mm (1 mm overlap)	4 × 1 mm
Radiation exposure (mSv)	—	1.7	6.5
In-plane resolution	≤1.0 mm	0.8 mm	0.6 mm
Slice thickness	>2.0 mm	1.5–3.0 mm	1.25 mm

techniques have been evolving ever since. Currently, two approaches are being used with respect to the data acquisition. The entire cardiac volume can be scanned in a long respiratory gated session (>10 minutes), or smaller targeted volumetric sections can be acquired, with a slightly lower resolution but within a single breath-hold (Figure 1). The acquisitions are synchronized to the cardiac cycle by means of prospective ECG triggering. The image signal from the coronary lumen can be enhanced by use of the flow-dependent MR acquisition sequences or by injection of MR-specific contrast agents. Considerable effort has been put into the development of so-called blood pool contrast agents, which remain in the bloodstream for an extended period and allow prolonged or repetitive contrast-enhanced acquisitions.

Electron Beam Computed Tomography

EBCT was introduced in 1983, and the first angiographic experiences were published in 1995. The short scan time is accomplished by replacing the mechanically rotating x-ray tube. Instead, an electron gun generates an electron beam that is guided along a 210° tungsten target ring in the gantry. X-rays are produced after the electrons strike the target ring, and a collimated fan beam is passed through the patient in the gantry. Opposite the target rings, a stationary 216° detector ring is positioned. The data for one tomogram can be collected in 50–100 milliseconds. The electron gun is triggered by the ECG, after which the patient is advanced one slice position in anticipation of the next acquisition. The maximum number of slices that can be collected within one breath-hold depends on the patient's heart rate and can be increased by intravenous administration of atropine (Table 1).

Multislice Spiral Computed Tomography

The current generation of MSCT scanners was introduced by a number of manufacturers in 1998. Although each detector configuration varies, all systems continuously acquire up to 4 slices at a gantry rotation time of 500 milliseconds. The collimated slice thickness measures 1 mm (Marconi/Philips, Siemens, Toshiba) or 1.25 mm (General Electric). Multislice sequential protocols are available, but spiral protocols are routinely applied for high-resolution coronary angiography. Because overlapping spiral data are acquired continuously, and synchronization to the recorded ECG is performed after acquisition of the CT data, transverse slices can be reconstructed at any longitudinal position and at any moment within the cardiac cycle. As mechanical scanners with rotating x-ray tubes, MSCT scanners have a relatively limited temporal resolution. Partial-scan reconstruction algorithms require data from only half a rotation (250 milliseconds temporal resolution) to reconstruct a slice. In an effort further to improve the temporal resolution at higher heart rates, multisegment reconstruction algorithms combine data from consecutive cardiac cycles.

Considerable effort has been put into the development of so-called blood pool contrast agents.

Potentially, the effective length of the reconstruction window per cycle can be reduced to 125 milliseconds or less if more than two cycles are integrated. The effectiveness, however, varies with the instantaneous heart rate at the time of data acquisition and requires a low table feed. At higher heart rates, motion artifacts are increasingly observed, and the

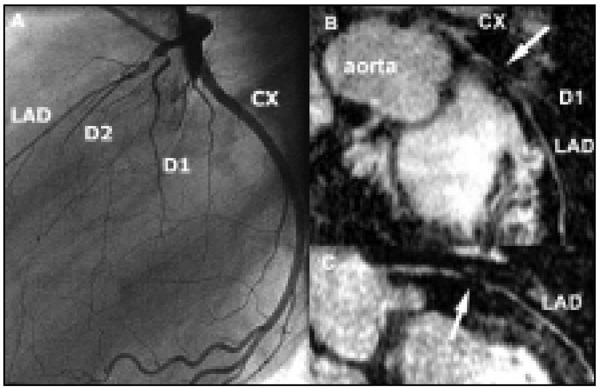


Figure 2. *Magnetic resonance (MR) coronary angiogram.* **(A)** *Conventional and* **(B and C)** *MR coronary angiogram of a patient with a significant stenosis in the left anterior descending coronary artery (LAD). CX, left circumflex; D1, first diagonal; D2, second diagonal branch.*

image quality significantly improves with the use of oral or intravenous β-receptor blocking agents. A 1 mm detector collimation protocol results in an effective slice thickness of 1.25 mm. In spiral scanning these slices can be reconstructed at an arbitrary increment. Usually, a reconstruction increment below the slice thickness is selected to create overlapping slices and improve the interslice correlation. For further technical details regarding the imaging modalities, see Table 1.

Computed Tomography Angiographic Examination

Both EBCT and MSCT coronary angiography are performed during a single breath-hold, and the coronary lumen is opacified by an intravenous injection of an iodine contrast medium. To optimize the contrast enhancement, a test bolus is generally performed to determine the transit time of the contrast medium. For prospectively triggered sequential acquisitions, the scan window is positioned within the ECG's R-to-R-wave interval prior to the data acquisition, whereas for retrospectively gated spiral acquisitions, the most appropriate reconstruction window position can be determined after data have been acquired. Typically, a position within the mid-to-end diastolic period is selected to minimize motion artifacts. Particularly at faster heart rates, the most optimal positions may vary per individual coronary branch.[1]

Magnetic Resonance and Computed Tomography Coronary Angiography

Each with their own advantages, breath-hold and respiratory-gated acquisitions has been able to visualize the proximal and middle coronary segments (Figures 1 and 2). Although very promising results in small study populations have been published, diagnostic accuracy in detecting stenotic lesions remains modest. A multicenter trial recently published by Kim and colleagues found that 84% of the proximal and middle segments were interpretable, with a reported sensitivity and specificity in detecting significant coronary stenosis (more than 50% lumen diameter reduction) in 83% and 73%, respectively.[2]

Although continuously improving, the overall spatial resolution and contrast-to-noise of MR are currently not sufficient. To create an image, most scanning sequences require averaging of data that are acquired during different cardiac cycles. Recently developed so-called *multi-slice true FISP* (fast imaging with steadystate precession) sequences acquire each slice during one cycle and may reduce MR's susceptibility to cardiac motion (Figure 1). Further technical developments, such as stronger magnetic fields, stronger gradients with faster rise times, and more effective radio-frequency receiver coils will improve the image quality and reliability of MR coronary angiography. One evident advantage of MR is the possibility of repeating an acquisition any desired number of times, whereas with CT a second acquisition will require additional exposure to radiation and contrast medium. Furthermore, the angiographic acquisition can be combined with assessment of the contractile function of the heart, the viability of the myocardial tissue, valvular disease, and so forth.

The image quality of a complete coronary examination, in terms of spatial resolution and contrast-to-noise ratio, is generally better in CT angiography, although at the

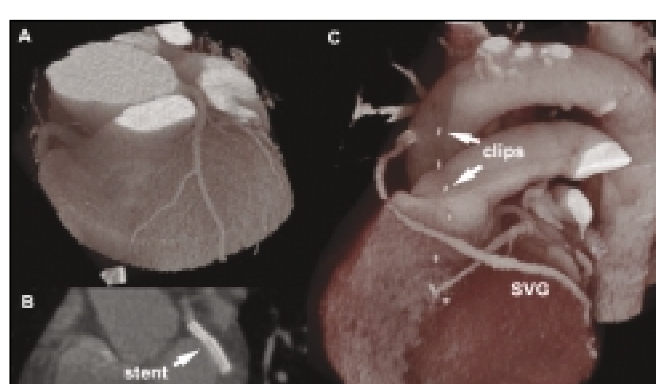


Figure 3. *Cardiac angiography with prospectively ECG-gated electron beam computed tomography (EBCT).* **(A)** *Volume-rendered EBCT coronary angiogram showing a nondiseased left coronary artery.* **(B)** *Multiplanar reconstruction of a stent in the left circumflex coronary artery.* **(C)** *Venous bypass graft (SVG) with partial stenosis of the proximal segment and occluded left internal mammary artery graft. Only the surgical clips around the nonenhanced graft are visible.*

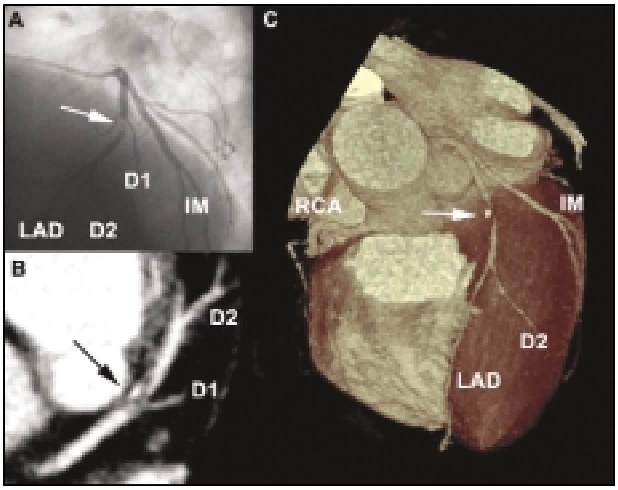


Figure 4. *Cardiac angiography with retrospectively ECG-gated multislice spiral computed tomography (MSCT). The stenotic lesion (arrow) at the bifurcation of the left anterior descending coronary artery (LAD) and first diagonal branch (D1) on the conventional angiogram* **(A)** *is also easily visible on the three-dimensional volume rendered MSCT angiogram* **(C)**. **(B)** *In addition to the luminal assessment, the MSCT angiogram (multiplanar reconstruction) shows that the lesion consists of both calcified and noncalcified tissue. RCA, right coronary artery; IM, intermediate branch; D2, second diagonal branch.*

expense of radiation exposure and contrast injection. A number of studies comparing EBCT angiography with the "gold standard" of x-ray angiography show that EBCT can visualize the proximal and middle coronary branches and detect coronary obstructions with a sensitivity and specificity ranging from 74% to 92% and 71% to 94%, respectively (Figure 3).[3–8]

Only a limited number of studies that compared MSCT with conventional coronary angiography have been published.[9,10] So far the subjectively improved image quality of the MSCT images is not reflected by these preliminary results (Figure 4). In vessels that were regarded as assessable in terms of image quality, the diagnostic accuracy is comparable to EBCT. A large number of segments, however, were excluded due to motion artifacts. Unlike in these two studies, most sites currently use β-receptor blocking agents in patients with fast heart rates to reduce motion artifacts and improve the assessibility of the MSCT angiograms.[11]

Both CT modalities suffer from the assessment-impairing artifacts caused by calcifications and other high-density structures, such as stents and surgical clips (Figures 3 and 5). From a practical point of view, patients with a high calcium score or known advanced coronary artery disease cannot be reliably examined. Particularly patients with extensively calcified plaques might benefit from an MR angiography, which is not hindered by these calcium deposits. Unlike the larger and relatively immobile vessels, the lumen within coronary stents cannot be visualized well. Except for larger-sized, proximally positioned stents, only the most central lumen can be visualized using CT. Patency of the stented segment can usually be assessed.

Besides the native vessels, coronary artery bypass grafts have been examined with MRI, EBCT, and MSCT (Figures 3 and 5). Patency of the grafts, the mere presence of luminal contrast, can reliably be assessed. Luminal assessment and the detection of stenosis are more feasible in the large-diameter venous grafts compared to the small arterial grafts. In both MR and CT modalities, the assessment of grafts is hindered by the presence of high-density or metal material such as surgical clips and sternal wire. Instead of complete visualization, MR and EBCT have been used to assess the patency of grafts by means of a dynamic contrast injection.

Coronary Calcium Screening

The presence of calcium in the coronary arteries is a marker for the presence of coronary arteriosclerosis and has prognostic value. It is regarded as a poor predictor of obstructive disease in symptomatic patients but seems useful to exclude coronary artery disease in patients with chest pain at the emergency ward.[12] In 2000 the American College of Cardiology/American Heart Association Expert Consensus Committee on EBCT for the Diagnosis and Prognosis of Coronary Artery Disease concluded that the presence of calcium in a coronary plaque nei-

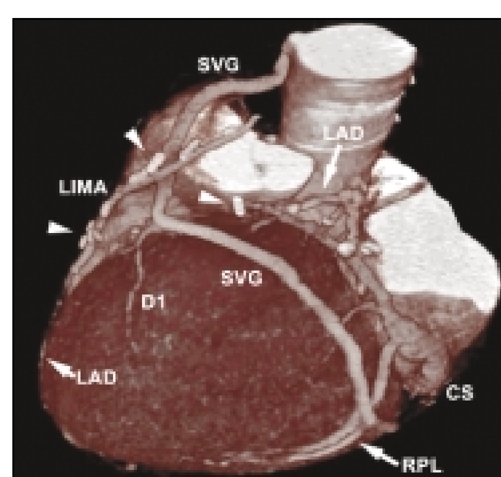


Figure 5. *Multislice spiral computed tomography angiogram after bypass surgery. Volume-rendered angiogram after bypass surgery. The left internal mammary artery (LIMA) is anastomosed with the small-diameter distal left anterior descending coronary artery (LAD). After supplying the diagonal branch (D1), the venous graft (SVG) continues to the posterolateral branch (RPL) and to the posterior descending artery (not visible from this angle). The proximal native coronary artery system as well as the cardiac veins, including the cardiac sinus (CS), are visualized well. The arrowheads indicate the surgical clips on the side branches of the LIMA.*

ther implies nor excludes plaque vulnerability; the coronary calcium score may be capable of identifying unstable or vulnerable patients.[13] The value of calcium screening in nonsymptomatic individuals, in additional to conventional risk factors and in comparison to other noninvasive screening methods, is still a matter of debate.[14]

Most experience in the field of coronary calcium quantification has been obtained with EBCT and the Agatston scoring method. Although intra- and interobserver variability is quite acceptable, interexamination variability ranges from 13% to 38%.[15] Instead of the semiquantitative Agatston scoring method, calculation of calcium volume seems to yield an improved reproducibility. By integrating the individual pixel densities instead of the maximum density value per lesion, the total calcium mass can be calculated.

Alternatively, MSCT can be used for calcium quantification in a spiral or sequential mode, the latter mode with a significantly lower radiation exposure. Most investigators have found a good correlation (92%–99%) between EBCT calcium scoring and various single- and multislice MSCT protocols.[16–18] Serial EBCT assessments have shown an annual increase of coronary calcium between 21% and 52%. Callister and colleagues showed with EBCT that statin therapy in patients with increased serum LDL levels but without obstructive coronary artery disease can decrease the progression of coronary calcium compared to untreated patients.[19] Similar results have been reported by other groups. If the interscan variations of the method can be improved, serial assessments of coronary calcium may become a valuable tool for monitoring progression of disease and evaluating response to the treatment both in clinical and research environments.

Functional Imaging

Compared to CT, MRI is a more versatile technique without health-related objections to serial examinations and therefore is more suited for a number of functional cardiac assessments. Cardiac cavity volumes, myocardial mass and stroke volumes, and ejection fractions can be calculated. Assessment of the contractile left ventricular function is accurate, highly reproducible, and therefore often regarded as the gold standard.

A fast-emerging application is so-called delayed contrast-enhancement imaging. If the heart is scanned 15 minutes after intravenous injection of a contrast agent, vital myocardium will no longer contain contrast; however, irreversibly damaged tissue will show increased enhancement. Because of the relatively good spatial resolution of delayed contrast-enhancement MR imaging compared to, for instance, positron emission tomography, transmural and subendocardial infarctions can be differentiated.

In a similar manner to pharmacologically induced stress echocardiography, MR can differentiate viable from nonvital scar tissue through injection of a low dose of dobutamine. Both the morphologic aspects and the hemodynamic characteristics, such as flow velocity, pressure gradient, and regurgitant flow quantification of valvular heart disease can be examined with MR. High-dose dobutamine imaging can be used for the detection of obstructive coronary artery disease. Coronary flow obstruction can also be detected by imaging the myocardial perfusion during injection of a contrast medium.

Using the 50-millisecond multislice mode of the EBCT scanner, several functional applications have been explored, including the left ventricular function. Using dynamic contrast injections, the patency of grafts and the perfusion of the myocardium can be assessed.

Spiral CT acquires data throughout the cardiac cycle, and slices can be reconstructed at any point within the R-to-R interval. The CT data acquired for the purpose of coronary angiography can be reconstructed during different cardiac phases to visualize regional wall thickness and then calculate the three-dimensional global ventricular function. Due to relatively poor temporal resolution, it is not possible to completely freeze the end-systolic phase, generally resulting in a systematic overestimation of the end-systolic volume and underestimation of the ejection fraction. Ventricular performance and other functional MSCT applications, such as myocardial perfusion, are currently being investigated.

Plaque Imaging

Histologic studies have shown that the composition of coronary plaques is of considerable importance with regard to the vulnerability of the lesion and the occurrence of an acute coronary syndrome. Invasive intracoronary techniques, such as intravascular ultrasound, ultrasound elastography, angioscopy, thermography, optical coherence tomography, near-infrared spectroscopy, and Raman spectroscopy are capable of distinguishing various histologic components, such as necrotic lipid pool, fibrous cap, thrombotic material, calcium deposits, and so forth. In the larger peripheral vessels such as the carotid arteries and the aorta, both contrast-enhanced CT and multicontrast MRI have been able to distinguish a number of plaque components. With MRI, it has been shown possible to monitor the effect of statins on carotid and aortic plaques.[20]

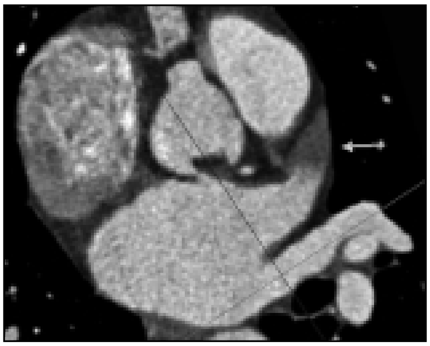


Figure 6. *Detection of a thrombi with multislice spiral computed tomography. A thrombus was detected in the left auricle of a patient with paroxysmal atrial fibrillation.*

The first attempts to visualize coronary plaques noninvasively and describe their contents in vivo have been published for both MR and MSCT.[21–23] The black-blood MR sequences provide high-resolution cross sections of the coronary wall. Currently, the scan time per image is too long to allow screening of extended sections of the coronary arteries. CT is not yet capable of showing the vessel wall with the same in-plane spatial resolution as MR. However, it is possible to screen, at a slightly lower resolution, the entire coronary system (Figure 4). At the current state of technical development, a combined use of CT and MR to respectively detect and characterize coronary plaques may be the most effective approach. Still, both techniques would benefit from an improvement of spatial resolution, particularly by reducing the slice thickness.

Miscellaneous Applications

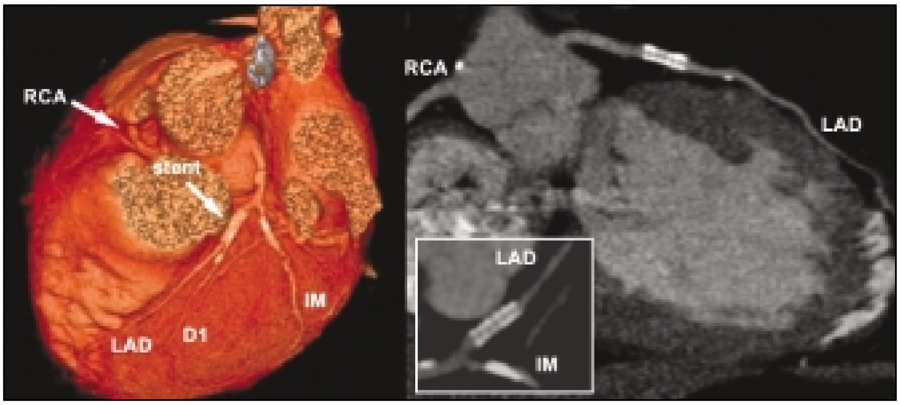
In various clinical situations, noninvasive angiography provides additional information or may substitute for conventional diagnostics in specific situations. Anomalous coronary anatomy can easily be visualized in a three-dimensional fashion. For mapping purposes prior to surgery, percutaneous intervention, or pacemaker placement, MR and CT are increasingly applied to provide a detailed road map, with clear advantages compared to conventional angiographic preparations. Tomographic techniques may become an alternative to transesophageal ultrasound for the detection of intracardial thrombi (Figure 6). In numerous situations, CT or MR can act as a substitute for echocardiography or Doppler ultrasound.

Future Developments

None of the noninvasive modalities MRI, EBCT, or MSCT is at the end of its technical development. Advancements in scanner technology and contrast media in the next few years will push MR applications, such as detection of viable myocardium and quantification of ventricular performance. Besides further reduction of scan time below 50 milliseconds, which has been announced by the manufacturer, EBCT will benefit from the implementation of more and thinner slices. Several CT manufacturers have introduced or announced the next generation of MSCT scanners, which will be equipped with an expanded number of thinner detector rows and shorter rotation time (Figure 7). Concerns regarding the radiation exposure of MSCT will be addressed by means of prospectively triggered x-tube modulation, which reduces the tube current during the systolic cardiac phase.

At present, assessment of noninvasive angiographic data is subjective and time-consuming. Interpretation of the tomographic or three-dimensional, rather than projectional, images requires some time and effort to get accustomed to. Measurement tools, such as those used in conventional x-ray angiography, to perform objective and quantitative assessments of stenosis severity are needed to improve the diagnostic confidence of noninvasive coronary angiography. By the time the diagnostic competence of these techniques is established, research efforts will focus on the benefit of noninvasive coronary angiography in clinical practice. From the current perspective, noninvasive angiography will be particularly useful to exclude coronary artery disease in patients with a relatively low likelihood rather than staging patients with a high likelihood of obstructive coronary artery

Figure 7. *Coronary angiography with submillimeter slice thickness. An early experience with a next-generation multislice spiral computed tomography scanner. By means of an increased Z-resolution, the effective slice thickness has decreased from 1.3 to 0.8 mm; the small-diameter stent can be visualized well* ***(right side)****. Using 12 slices at a reduced rotation time of 0.42 seconds, data acquisition was accomplished in less than 25 seconds. LAD, left anterior descending coronary artery; RCA, right coronary artery; IM, intermediate branch; D1, diagonal branch.*



disease. Instead of repeated catheterizations, these techniques would be an attractive means to follow up on progression of disease and response to therapy. Although a considerable amount of work needs to be done and new technical innovations are being introduced around the clock, clinical implementation of at least a number of these new and noninvasive applications seems inevitable and will change the field of cardiovascular medicine. ■

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Main Points

- Coronary arteries are never completely immobile, but motion is limited during the mid-to-end diastolic phase, so data acquisition or image reconstruction should be limited to this period.
- With computed tomography modalities, the entire heart needs to be covered within the time of a single breath-hold to avoid multiple contrast injections.
- Currently used magnetic resonance imaging (MRI) systems and scan protocols do not pose health hazards, and the use of contrast agents is optional.
- MR-specific contrast agents such as blood pool contrast agents remain in the bloodstream for an extended period and allow prolonged acquisitions.
- Multislice spiral computed tomography (MSCT) acquires overlapping spiral data continuously, and transverse slices can be reconstructed at any longitudinal position and at any moment within the cardiac cycle.
- MSCT scanners have a relatively limited temporal resolution, but partial-scan reconstruction algorithms require data from only half a rotation to reconstruct a slice, and multisegment reconstruction algorithms can combine data from consecutive cardiac cycles and can improve the temporal resolution even further.
- Patients with a high calcium score or known advanced coronary artery disease cannot be reliably examined with CT methods; patients with extensively calcified plaques might benefit from an MR angiography.
- In delayed contrast-enhancement imaging, the heart is scanned 15 minutes after intravenous injection of a contrast agent; vital myocardium will no longer contain contrast but irreversibly damaged tissue will show increased enhancement.