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Coronary Computed Tomographic Angiography

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Catheter-based coronary angiography has played a central role in the evolution of cardiology since it was first developed over 50 years ago. The procedure provides a detailed examination of coronary anatomy and is the gold standard for the diagnosis of obstructive coronary artery disease (CAD), serving as the roadmap for bypass surgery and percutaneous coronary intervention (PCI). Coronary angiography has also provided numerous insights into the biology of coronary atherosclerosis, including the natural history of CAD, the pathophysiology of acute coronary syndromes, and the mechanisms of anti-atherosclerotic therapies such as statins.[1] However, catheter-based coronary angiography is an invasive procedure with a small risk of serious complications. This potential for adverse effects has limited its clinical use to selective circumstances and stimulated the development of noninvasive functional alternatives for the diagnosis and follow-up of CAD, such as stress perfusion imaging.

Despite efforts over 20 years to achieve noninvasive anatomic assessment of the coronary arteries, progress had been disappointing. In contrast to vessels in the brain or peripheral circulation, coronary arteries are smaller (2 to 4 mm), subject to constant cardiac and respiratory motion, and follow a complex 3-dimensional anatomic course. Recent developments in computed tomography (CT) technology have now, in selected circumstances, made it possible to reliably overcome these challenges and produce diagnostic quality images. There is little doubt that we are on the threshold of the clinical implementation of a noninvasive alternative to coronary angiography. This issue of *Cardiology Rounds* describes the technology behind coronary CT angiography and the evidence for present and future imaging.

Fundamentals of cardiac CT

The basic image in a CT scanner is generated by an x-ray tube and a detector. The x-ray tube is the source of radiation. The detector is opposite the x-ray tube and is composed of scintillation crystals that capture the incident x-rays and ultimately produce the CT image. Both detector and x-ray tube are mounted on a gantry that rotates about the patient (Figure 1). In helical CT scanning, the gantry rotates continuously with simultaneous longitudinal (or Z axis) patient motion, generating a helical course for the detector in relation to the patient. The primary technical improvements that have made coronary imaging possible are faster gantry rotation speeds, increasing numbers of detectors with submillimeter collimation, and more sophisticated post-processing techniques.

Improved gantry rotation time has allowed for more rapid image acquisition and a reduction in motion artifacts (Table 1). When first developed, a helical scanner had a gantry rotation time of 1000 milliseconds (msecs).[2] This has been reduced to 420 msecs on currently available scanners. The application of retrospective ECG-gating allows for the reconstruction of an entire scan dataset at a given point in the cardiac cycle. The temporal resolution (data acquisition window) for the scan has been reduced to between 50 to 210 msecs, resulting in a substantial reduction of cardiac motion artifacts. In general, motion-free images can be reliably obtained, especially when the patient's heart rate is <60 bpm. Thus, pre-scan beta-blockade has been an important adjunct for high quality imaging.

Increasing data channels allow for the use of an increasing number of detector rows for data acquisition and have shortened scan time, since more slices are acquired for each gantry rotation.

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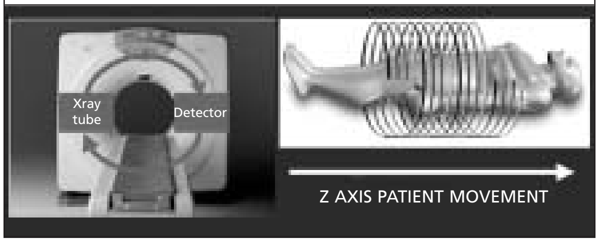
Figure 1: Basic image in a CT scanner is generated by an x-ray tube and detector, mounted on a gantry that rotates about the patient



Detector width and, hence, minimum slice collimation have improved to the submillimeter range, dramatically improving the spatial resolution of the images in the longitudinal axis (Table 2). With 16-channel multidetector scanners, the resolution in the longitudinal axis matches the resolution in the axial plane[2] for the first time, resulting in a truly isotropic imaging voxel. This represents an important change in coronary imaging with CT because images can now be viewed as a true volume of data with similar resolution (approximately 600 µm) in any standard or user-specified plane.

Even with contemporary scanners, there are several important limitations to coronary CT angiography. Visualization of the lumen adjacent to heavily calcified plaques is limited. Vessels <2 mm (usually distal coronary branches) cannot be reliably evaluated, although they are generally below the size addressed by revascularization techniques. Patients receive a radiographic contrast dose and radiation exposure that is similar to catheter angiography.

CT technology continues to develop rapidly and improvements on the horizon will further increase both spatial and temporal resolution. This year, the first installation of the next generation of scanners will be implemented in select centres around the world. These scanners will have gantry rotation times of 370 msecs and 64 channels of data acquisition. The isotropic resolution is 400 µm and imaging of the entire heart can be performed in 7 seconds. It is likely that the clinical results with this next generation of scanners will be better than those already achieved with the 16 detector scanners discussed below.

Table 1: Substantial improvements in temporal resolution and motion artifacts have been achieved with advancements in CT scan technology

	1989	1998	2002
Gantry rotation	1000 msecs	500 msecs	420 msecs
Temporal resolution	250 – 500 msecs	125 – 250 msecs	50 – 210 msecs
Motion artifacts	100%	50%	10%

Table 2: As the number of detectors increased from "1" to "16", there have been improvements in in-plane resolution, slice thickness and resolution in all 3 planes

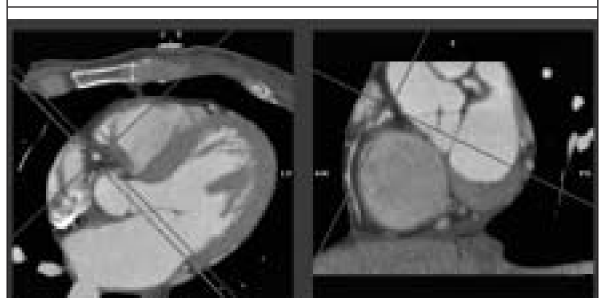
	1989	1998	2002
In-plane resolution	0.6 x 0.6 mm	0.6 x 0.6 mm	0.6 x 0.6 mm
Slice thickness	3 mm	1-1.25 mm	0.625 mm
Detectors	1	4	16
Spatial resolution	0.6x0.6x3 mm	0.6x0.6x1 mm	0.6x0.6 x0.6 mm Isotropic

Image display and interpretation

Upon the completion of scanning, a volumetric dataset is generated for image analysis. The process of coronary CT angiography interpretation involves interrogating this volume of data with the aid of a 3D imaging-viewing workstation to gain information about the anatomy and pathology of the coronary arteries. For this purpose, multiple visualization tools are used to evaluate each arterial segment. Visualization techniques include multi-planar reformats (MPRs), maximum intensity projections (MIPs), and 3D volume rendering (3DVR).

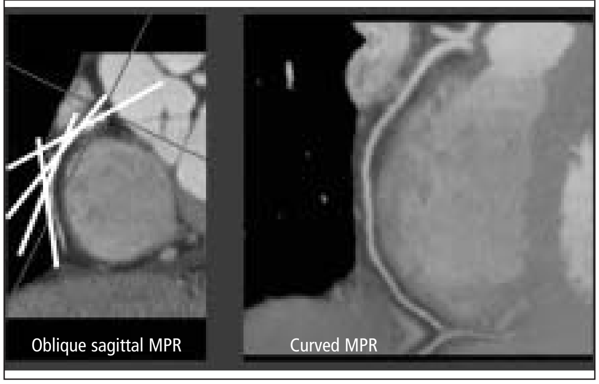
Basic image interpretation can be performed on axial slices taken through the heart. In addition to the standard axial plane, any user-specified oblique plane can be viewed. These are called multiplanar reformats or MPR images (Figure 2). Since the coronaries have a curved orientation around the heart, it is usually not possible to demonstrate a significant length of a vessel on a single MPR slice. In order to visualize longer segments of vessels, a curved multiplanar reformat can be produced using data from multiple slices in various angles (Figure 3). An alternative method is to generate a projectional image by summing data from multiple slices taken through a specified spatial orientation. This technique, called "maximum intensity projection" or

Figure 2: Image interpretation can be performed with single slice data in any plane (standard transverse, coronal, sagittal, or any oblique); these are called multiplanar reformats or MPR images



Oblique transverse MPR (Int/Rt view) Oblique sagittal MPR (Lft-Ant view)

Figure 3: **To visualize curved coronary arteries, a curved multi-planar reformat image uses data from multiple slices in various angles**



MIP, displays the brightest point from the stack of slices on the final image (Figure 4). A final image analysis tool is 3-dimensional volume rendering that is most helpful as a global overview of anatomy, but not for detection of stenoses (Figure 5). Data is acquired continuously throughout the cardiac cycle so that gated analyses of ventricular function and wall motion are also possible, as is anatomic evaluation of cardiac chambers and the pericardial apparatus. In addition, since a coronary CT angiography is essentially an ECG-gated contrast-enhanced CT of the chest, it may yield other information pertinent to patient management related to pulmonary, mediastinal, spinal, or thoracic wall abnormalities. A review of all imaged structures is necessary in the study interpretation.

Normal coronary anatomy

The panel of figures (Figure 6A to 6F) demonstrates selected MIPs of a patient with normal coronary arteries.

- Figure 6A shows the left main ostium and bifurcation of the left anterior descending (LAD) and left circumflex arteries.

Figure 4: **Maximum intensity projection (MIP) sums data from multiple slices taken in the same orientation and allows vessel visualization over a longer segment.**

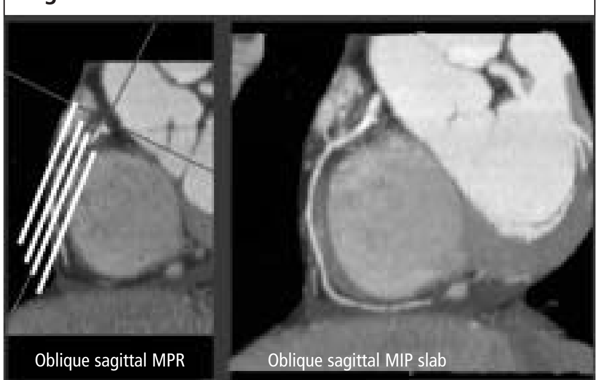
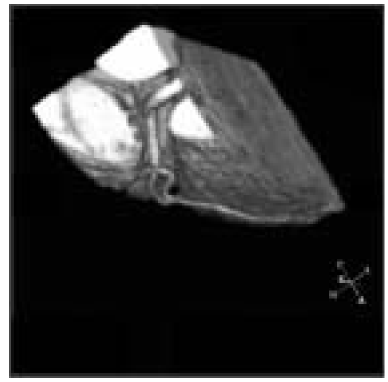


Figure 5: **3D volume rendering is useful for a global overview of anatomy**



- Figure 6B shows a long axis view of the proximal and mid-LAD.
- Figure 6C shows the left circumflex artery in the left atrioventricular groove with a large obtuse marginal branch.
- Figure 6D demonstrates the ostium and proximal portion of the right coronary artery (RCA).
- Figure 6E shows the mid-RCA in the right atrioventricular groove. Figure 6F shows the distal RCA and posterior interventricular artery (PIV). The lower density vascular structures in the image are cardiac veins.

Evolving indications

The vessel lumen: detection of coronary stenoses

The primary goal in the clinical development of coronary CT angiography has been the reliable detection and evaluation of coronary stenoses. Figure 7 shows sample images of a patient with a significant RCA stenosis by CT and catheter angiography. Validation studies comparing CT and catheter angiography were first published in 1998. They can be divided between those performed on 4 detector and 16 detector scanners. With 4 detector scanners, arteries could not be evaluated in up to 30% of patients; this has been reduced to around 10% with 16 detector scanners.

Figure 6: **Selected MIPs in normal coronary arteries (see text)**

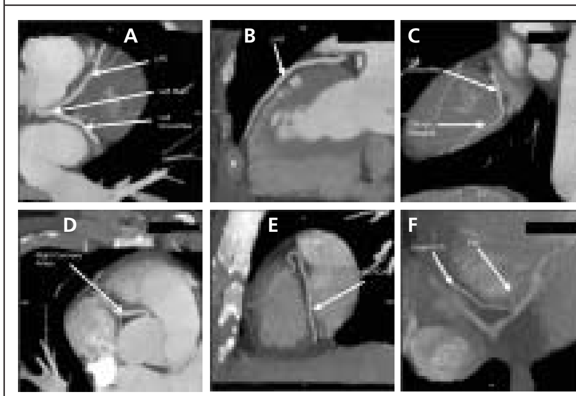
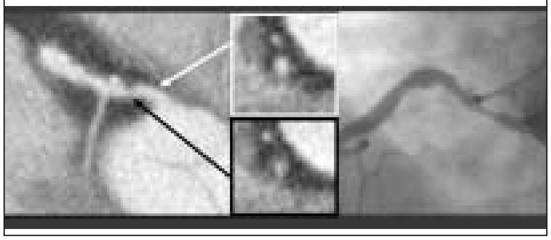


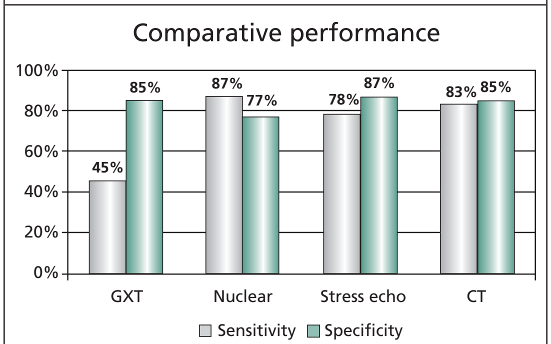
Figure 7: **Images of RCA stenosis with CT and catheter angiography**



Diagnostic performance has also improved with 16 detectors. In a recently presented meta-analysis, sensitivity and specificity for the detection of luminal stenoses >50% were 83% and 85%, respectively.[3] Compared to the test characteristics of other non-invasive diagnostic techniques for the evaluation of potential coronary disease, CT angiography has comparable test performance (Figure 8). An important difference is that CT angiography provides anatomic rather than functional information. It is therefore complementary to the other noninvasive functional imaging modalities.

Much knowledge has been acquired even in the short time since these studies were completed. The most contemporary results, achieved at one of the most experienced centres in the world, were recently published.[4] The authors studied 128 patients who were beta-blocked, where necessary, to achieve a mean heart rate of 58 bpm. The patient group had typical angina and was similar to a general catheterization referral population. No significant disease was found in 17%, 1-vessel disease was found in 35%, 2-vessel disease in 35%, 3-vessel disease in 14% and 5% had left main artery disease. Vessel by vessel, the sensitivity and specificity for detection of >50% stenoses by quantitative coronary angiography was 94% and 91%, respectively. All left main lesions and total occlusions were identified. Overall, the sensitivity and specificity for a classification of patients with or without obstructive CAD was 100% and 86%, respectively. The positive and negative predictive values in this patient population, which had a relatively high prevalence of disease, were 97% and 100%, respectively.

Figure 8: **Comparison of CT angiography with other noninvasive diagnostic techniques**



ACC/AHA Guidelines (Echo, Nuclear, Stress Testing) and Hoffman, ACC, 2004

Since CT angiography has excellent negative predictive value, it may prove to be especially valuable for excluding CAD in patients with a low to intermediate pretest probability of disease. It may also be a useful alternative to catheter angiography when other noninvasive testing is inconclusive or symptoms are atypical. A negative noninvasive exam could avoid the need for catheterization (Table 3).

In patients with extensive CAD, CT angiography is limited by extensive calcification that makes luminal assessment more challenging. Furthermore, because imaging is performed with a single nonselective bolus of contrast, collateral circulation cannot be evaluated. Therefore, CT angiography offers less diagnostic information in patients with advanced coronary atherosclerosis. However, as diagnostic performance improves, it is likely that CT angiography will perform an increasing number of catheter angiography functions. Ultimately, the "roadmap" of significant coronary disease and the follow-up of disease progression may be determined noninvasively, with many patients entering the catheterization laboratory only to undergo planned revascularization procedures.

Post-revascularization

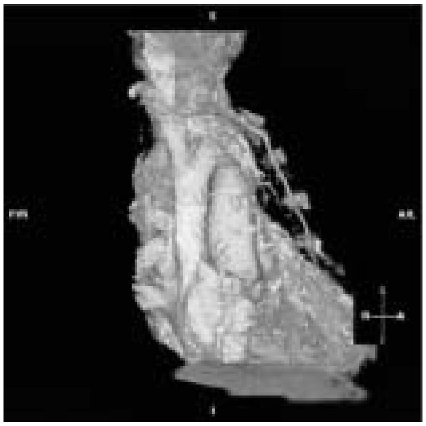
Coronary bypass grafts are larger and have less motion than native coronary arteries, and can be more reliably imaged. Patency of both saphenous vein grafts and arterial conduits can be evaluated with CT angiography. Figure 9 shows a patent saphenous vein graft to the right coronary artery. The proximal anastomosis is seen in the ascending aorta, although the distal anastomosis is not seen in this projection.

With the availability of drug-eluting stents, more complex lesion subsets are being treated percutaneously. When stenting is performed in the most proximal vessels (left main or ostial LAD), it is often interesting to perform surveillance angiography to assess the continued patency of the stent. Although

Table 3: **Candidates for CT coronary angiography**

- Heart rate < 80, ideally < 60
- Intermediate to low probability of significant coronary artery disease
- Lack of extensive vessel calcification
- Normal renal function

Figure 9: **CT angiography of patent saphenous vein graft to the right coronary artery**



not systematically studied, CT angiography may distinguish between patent and occluded stents that are ≥3 mm. Figure 10 shows pre- and post-intervention angiograms in a patient who underwent left main stenting at St. Michael's Hospital using a crush technique that places separate stents from the left main to the LAD and left main to left circumflex. The 3DVR image shows both stents. The MPR shows patency of the left main to LAD stent. Active research is being conducted to see if CT angiography can evaluate the patency of coronary stents and the presence of in-stent restenosis.

Future developments

The vessel wall: evaluation of subclinical atherosclerosis

Although all imaging modalities for the assessment of CAD provide direct or indirect information on the presence of coronary stenoses, only CT and potentially MRI have the ability to visualize the vessel wall and provide information on the atherosclerotic process itself in a noninvasive manner. This area of development is still fairly new, but several features of plaque can be assessed by CT, including the presence of nonobstructive calcified and noncalcified lesions.

The first and most widely applied modality for atherosclerosis assessment with CT is the coronary calcium score. The extent of calcification is measured by summing calcification detected on each slice. It has been well demonstrated that the total calcium score is a marker for the extent of coronary atherosclerotic disease burden. Epidemiologic studies have shown that calcium scores can predict future cardiac events in asymptomatic individuals. However, there has been substantial controversy about the added value of calcium scoring above the information already provided by the Framingham Risk Score. Data on this issue from a 7-year prospective cohort study have recently been published.[5] The study showed that in patients at intermediate risk by Framingham criteria (10-year event rate of 10% to 20%), there was a modest further separation of cardiac event rates using the calcium score, particularly for scores >300 (Figure 11).

Another important finding of this study was that, in all Framingham risk categories, events were still seen in patients who had a "0" calcium score. This implies that additional noncalcified plaques are present and are missed by this technique that images calcium only. Very recent work with contrast-enhanced CT angiography suggests that such noncalcified plaques can also be detected and quantified.[6] Figure 12 displays multidetector spiral computed tomography (MDCT) images with a correlation to intravascular ultrasound (IVUS) images, the current gold standard for detection of coronary atherosclerosis. The images at the top are of an MDCT of the proximal LAD demonstrating plaque of low attenuation at the

Figure 10: **Pre- and postintervention angiograms of left main stenting using a crush technique**
Top left: pre-intervention; Top right: post-intervention; Bottom left: 3DVR image; Bottom right: post- intervention MPR

Figure 11: **There is a modest separation of cardiac events using the coronary artery calcification score (CACS), particularly for a score >300, however, events still occur in patients with a "0" score.**

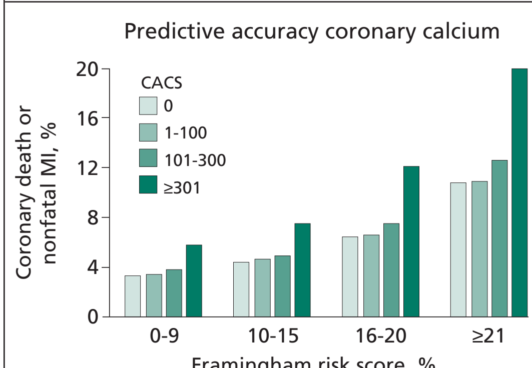
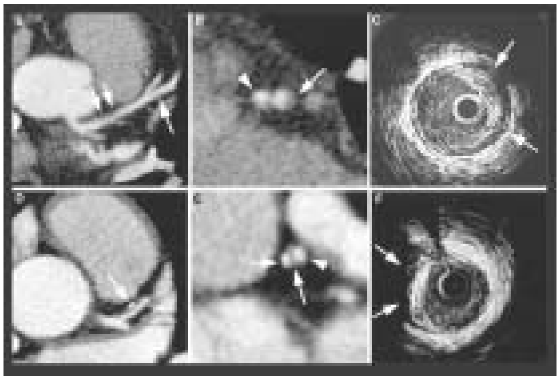


Figure 12: Multidetector spiral computed tomography images (MDCT, top panel) correlated with intravascular ultrasound (IVUS, bottom panel) in detecting nonstenotic lesions



bifurcation of the LAD and the diagonal. In the short axis, the diagonal is on the left, and on the far right, the low attenuation plaque in the LAD is seen. This corresponds to the IVUS image that demonstrates plaque in the same location. In the bottom panel, a calcified plaque is seen on both the MDCT and IVUS images.

Assessment of the vessel wall by CT is a very active area of research. Efforts are being made to quantify the extent of coronary plaque. In addition, features of plaque vulnerability, as detected by CT, are being explored including the extent of vessel remodeling and coronary plaque content. The ultimate goal of these efforts is to develop a noninvasive assessment of the total calcified and noncalcified coronary plaque burden (a coronary "plaque map") and to identify particularly high-risk coronary lesions by morphologic criteria.

Conclusion

Recent developments in CT technology now allow for reliable imaging of coronary arteries in selected patient groups and, in the future, CT angiography may provide an assessment of the burden and significance of subclinical atherosclerotic plaque. Coronary CT angiography will be of increasing worth in the evaluation of coronary stenoses and will play a growing role in the management of patients with CAD.

Images in Figures 4-8, and 12 have been provided courtesy of the Division of Cardiovascular Imaging, Department of Radiology, Brigham and Women's Hospital/Harvard Medical School. CT images in Figure 13 are provided courtesy of Department of Radiology, Northhumberland Hills Hospital, Coburg, Ontario.

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