Imaging the coronary arteries with CT

Advancing CT technology

In the 1980s CT imaging of coronary arteries began after the introduction of electron beam CT (EBCT), with the main application being quantification of calcifications in the coronary arteries for risk stratification. In the late 1990s helical multidetector row CT (MDCT), starting with the four-detector row, was used for noninvasive evaluation of suspected coronary artery disease. Initially MDCT had limited performance for visualising coronary arteries due to long scan time, with the required breath-hold often exceeding 30 seconds. The scanners had a long rotation time with limited temporal resolution of 250ms and x-ray beam coverage of approximately 8mm (four detector rows, each of 2mm thickness), insufficient for motion-free coronary imaging. Clinical performance improved considerably with the introduction of firstly 16-detector row MDCT, followed by 64-detector row CT. The new scanners could perform helical acquisition of coronary arteries within one breath-hold (less than 15 seconds), with increased x-ray beam coverage up to 40mm and reconstructed slice thickness down to 0.5mm with improved temporal resolution.

Helical cardiac MDCT, in contrast to regular helical scanning, has a very low pitch and is acquired over several cardiac cycles with electrocardiogram (ECG) signal recorded simultaneously. A very low pitch requires very low table speed to scan the heart during one complete cardiac cycle. The recorded ECG is used to select, or gate, the scan data corresponding to cardiac rest phase, which is the phase interval with least motion blurring – termed retrospective reconstruction. Retrospective ECG-gated reconstruction allows not only the cardiac rest phase, but any cardiac phase to be reconstructed; thus, the phase with the least motion can be selected retrospectively and, when necessary, additional phases can be reconstructed to obtain optimised diagnostic image quality for each coronary artery independently (figure 1). In addition, reconstructions at the end-systolic and end-diastolic phases can be made to evaluate ventricular function (figure 2).

The wider beam coverage allowed introduction of sequential prospective triggering acquisition of the heart. This so-called step-and-shoot allowed coverage of the entire heart in three to five shots and the ECG signal is used to trigger the axial acquisition at exactly the desired cardiac rest phase. This technique allows a decrease in radiation exposure of 80%. Data is acquired during a specific, predefined cardiac rest phase. At a low and stable heart rate, the mid-diastolic phase is optimal for coronary artery evaluation, usually at 65-75% of R-R interval. At higher heart rates (>65 beats per min) the phase with least coronary motion is often end-systolic phase, usually at 35-40% of R-R interval (figure 3).

Recent technical advances include dual-source CT scanners equipped with two x-ray tubes (and two detectors) at 90° to each other. By combining information from both detectors, images are reconstructed with a temporal resolution corresponding to only a quarter of the rotation of both detectors with a gantry rotation time of 330ms. Temporal resolution thus improves to 330/4=83ms, and with the second-generation dual-source CT scanners, temporal resolution of 75ms is achieved. However, dual-source CT still relies on a helical acquisition. Another innovation is development of volume CT with 320 detector rows. The volumetric CT scanner covers 160mm and thus allows the entire heart to be scanned in a single axial acquisition that takes only a fraction of a second. Volumetric axial CT allows dose reduction to be achieved, short scan times resulting in less arrhythmia related artifacts and use of smaller volumes of contrast material.

Coronary CT angiogram optimisation

Patient preparation

During pre-assessment a combination of letter, phone call and/or pre-assessment clinic is utilised to reduce anxiety, address challenging issues (eg use of translator or difficulty elevating arms) and to explain the procedure, ie lying flat for 15 minutes, breath-hold for 10-15 seconds and side-effects of intravenous contrast, β-blockers and sublingual GTN. In addition a list of medications and allergies is obtained in order to check drug interactions. Patients are instructed to avoid caffeine and smoking 12 hours before the procedure to avoid cardiac stimulation. They are also instructed to avoid eating solid food four hours before the study and increase their fluid intake. Standard precautions regarding contrast allergy history and renal function are also taken.

Usually as part of the preparation β-blockers are utilised to lower heart rate in order to reduce motion artifact. Lowering heart rate level depends upon the temporal resolution of the scanner; with single-source CT the heart rate should be below 65 and ideally below 60 beats per minute while with dual-source CT heart rate variability is a more important determinant of image quality. Beta-blockers are helpful to lower heart rate but also have a negative chronotropic effect, lengthening diastole. Beta-blockers are contraindicated when heart rate is below 60 or there is evidence of second or third degree AV block, sick sinus syndrome, systolic BP <95mmHg, severe asthma, or active bronchospasm, decompensated cardiac failure, pheochromocytoma (can be given in combination with α blocker). They can also be administered with caution in severe peripheral vascular disease and in combination with Ca-channel blockers. Oral metoprolol is effective after one hour, reaching peak plasma concentration after 60-90 minutes. Intravenous metoprolol has a peak effect at 5-10 minutes after administration. Atenolol and esmolol can also be used successfully. Diltiazem or verapamil can be used when β-blockers are contraindicated, however they are less effective and can result in hypotension. Many different protocols for administration of metoprolol can be used, for example, an oral dose of 50-100mg 60-90 minutes before the study followed by 5mg doses of IV metoprolol administered at 2-5 minute intervals, up to a total dose of 30-40mg, in order to achieve desired heart rate control.

There is emerging evidence of the effectiveness of an anti-anginal drug known as ivabradine, which acts directly on the sinoatrial (SA) node. Ivabradine is generally used as a second or third line treatment of stable angina and inappropriate sinus tachycardia NYHF II-IV. Ivabradine has few side effects including luminous phenomena. In the setting of the pre-assessment clinic, loading with oral ivabradine for 48 hours can be effective in achieving optimal heart rate control.

Just prior to the start of scanning, sublingual nitro-
glycerin is used to dilate coronary arteries in order to aid side branch visualisation. Importantly phosphodiesterase inhibitors must be omitted 48 hours prior to the study and the main contraindications are severe aortic stenosis, hypertrophic obstructive cardiomyopathy and low BP with systolic pressure less than 90mmHg.

Rhythm strip
Optimised rhythm strip is essential to ensure the R-wave is clearly visible and of sufficient amplitude for ECG gating. ECG lead placements must be outside the central field of view to avoid streak artefact. The ‘RA’ lead is over the right superior-lateral chest wall. The ‘LL’ lead is over the left infero-lateral chest wall and provides alignment along cardiac electrical axis. Finally the ‘LA’ lead is over the right infero-lateral chest wall. This arrangement aligns electrodes along the cardiac electroaxial axis. In the case of low signal, electrode placement must be checked and alternative positions chosen to ensure good R-wave amplitude (figure 4).

Breath-hold instructions
For coronary artery assessment, image acquisition should be at end-inspiration. However, for pulmonary vein mapping image acquisition is optimal at end-expiration.

Contrast bolus
Optimised contrast bolus concentration is essential and contrast concentration of 350mgI/mL and ideally 370-400mgI/mL will allow optimal opacification of coronary arteries to allow more accurate plaque assessment. As a principal, the rate of bolus injection should be higher for shorter scan times and for larger patients. Thus, for a 32-slice scanner a rate of 4-5ml/sec is satisfactory whereas for a 64-slice scanner a rate of 5-6ml/sec should be used. Larger patients require a higher rate of 5-7ml/sec. Impaired cardiac output results in high contrast enhancement and a delay to peak enhancement.

In order to achieve optimal opacification, delivery of a tight bolus of contrast is required in to the coronary arteries. To achieve this, a mixture of contrast and saline is administered either as a single-phase contrast followed by saline flush or a biphasic approach with bolus of contrast followed by admixture of saline and contrast followed by saline flush. The single-phase injection allows rapid washout from the right heart and superior vena cava thus eliminating streak artefact thus allowing better visualisation of the right coronary artery. The biphasic injection maintains right ventricular opacification thus allowing better detection of septal wall and is superior for functional assessment (figure 5). There are two methods used to deliver contrast bolus while monitoring aortic contrast enhancement at the carina (figure 6).

Image acquisition
The coronaries are optimally imaged during least cardiac motion, which occurs during so-called rest periods. This is typically mid-diastole (diastasis) and end-systole (isovolumic relaxation). The latter is of shorter duration than diastolic diastasis at low heart rates. Thus the 65-75% R-R interval (diastolic) can be optimal for all of the coronary arteries and additionally the 35-40% systolic window may be helpful for optimisation of right coronary artery (figure 7). As the heart rate increases, diastole shortens relative to systole, and diastasis shortens dramatically. Optimal reconstruction windows become 85-90% during diastole and 40-45% during systole. The use of a fixed reconstruction window millisecond rather than percentage of R-R may be helpful with variable R-R intervals, specifically in sinus arrhythmia or atrial fibrillation.

Clinical applications
Cardiac MDCT has become ubiquitous and, with generally good performance, has emerged as an appropriate diagnostic test in patients with a low-to-intermediate pretest probability for coronary artery disease. CT coronary artery calcium is appropriate for risk assessment for patients with intermediate pretest probability and in low pretest probability with a positive family history of premature cardiovascular disease (figure 8). The test has a high negative predictive value of 95-97%.

CT coronary angiogram (CTCA) is appropriate in symptomatic low-to-intermediate pretest probability after initial risk evaluation. Its major strength is ruling out coronary artery disease (figure 9). The UK National Institute of Clinical Excellence (NICE) guideline statement describes CTCA as a highly reliable and reproducible non-invasive test for chest pain of recent onset (figure 10). Furthermore the guidelines specifically state that exercise ECG should not be offered as a primary diagnostic test for myocardial ischaemia (figure 11a-b). It is important to recognise CTCA is not recommended in asymptomatic patients or patients with very low or high pretest probability.

Coronary artery bypass grafts are relatively easily assessed with good accuracy, however, when it comes to coronary artery stents CTCA has a limited ability of in-stent lumen evaluation due to stent characteristics and is limited by spatial and temporal resolution of CT, especially in stents with diameters less than 3mm (figure 12). There is a limited role for triple rule out in clinical practice owing to CT-related technical and patient-related clinical restrictions but it may be useful as a problem-solving tool.

Other applications include ventricular function analysis with global LV and RV function, which can be obtained with high diagnostic accuracy. Left ventricular regional wall motion abnormality can also be assessed but remains inferior to cardiac MR. Cardiac MDCT has limitations in valvular assessment due to its inability to directly measure flow velocity and volume across valves. Aortic and mitral valve can be assessed with reasonable accuracy (figure 13), however coronary artery and valve pathology is difficult to assess due to thinner valve leaflet. Finally, in terms of congenital heart disease, cardiac MDCT is useful in diagnosis and follow-up, especially when ECG is limited diagnostically and MRI is contraindicated.

References
11. ACCF/AHA/ASNC/NASCI/SCAP/SCCT 2010 expert consensus document on corro...
Figure 1
Volume scan acquisition modes.

Figure 2
Motion graph against phase of cardiac cycle.

Figure 3
Select optimal phase reconstruction.

Figure 4
ECG electrode placement.

Figure 5
Two different methods of contrast delivery.

A. Test bolus method
- 10ml bolus contrast at 5ml/sec followed by saline
- Sequential ungated axial images at two second intervals
- Breathing instructions constructed to extend for 10 seconds
- Total contrast transit time = 10 + 2 × (no. images reach peak enhancement at two second intervals)
  - advantage: trial contrast run
  - disadvantage: use of more contrast and additional time

B. Bolus track method
- A series of low dose axial scans every two seconds
- Track entry of contrast into descending aorta
- Predefined threshold (HU 180) reached – start scanning

Figure 6
Two methods monitor aortic contrast enhancement at Carina: (a) test bolus method and (b) bolus track method.

Figure 7
Diagrammatic representation of prospective gated image acquisition.
Low (10-30%)
- Offer CT coronary calcium
  0 Investigate other causes of chest pain
  1-400 offer CT angiogram
  >400 offer angiogram

Moderate (30-60%)
- Offer non-invasive functional imaging
  1. Myocardial scintigraphy with SPECT
  2. Cardiac MR perfusion or stress
  3. Stress echo
  note: echo poses particular problems with poor sensitivity

High (60-90%) and uncertain diagnosis
- Offer invasive angiography
  – if revascularisation considered
- Consider CTA or functional imaging
  – if revascularisation not considered or clinically inappropriate or unacceptable to patient

Figure 11b
NICE Guidelines – Pre-test probability chest pain. NICE guidance.11

Stent types and artifacts.

Figure 13
Calcified leaflets
Restricted opening

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