Noninvasive Coronary Artery Imaging:
Current Clinical Applications

These guidelines were revised by Dr Gary Liew, Profs Michael Feneley and Stephen Worthley on behalf of the Imaging Subcommittee of the CSANZ.

The guidelines were reviewed by the Continuing Education and Recertification Committee and ratified at the CSANZ Board meeting held on Friday, 26th November 2010.
Summary Points

1. Multidetector computed tomography (MDCT) is currently the preferred noninvasive modality that can reliably image coronary arteries.

2. Cardiac magnetic resonance imaging (MRI) has limited indications, including assessing suspected coronary anomalies and assessing complex congenital heart disease in expert centres.

3. The strength of MDCT is to rule out significant coronary artery disease (CAD) in a low-intermediate risk population with symptoms. This has been demonstrated in multi-centre trials.

4. Other appropriate indications for coronary CTA include:
   a. Investigation of equivocal or uninterpretable stress tests;
   b. Evaluation of suspected coronary anomalies / complex congenital heart disease;
   c. Evaluation of new onset heart failure / cardiomyopathy of unknown aetiology;
   d. Mapping of coronary vasculature including internal mammary arteries before repeat CABG;
   e. Evaluation of left bundle branch block;
   f. Excluding significant CAD before non-coronary cardiac surgery.

5. It is not appropriate to perform coronary CTA on patients who have known significant CAD or a high pre-test probability of CAD.

6. Use of MDCT to evaluate acute chest pain in the emergency department has been studied in a number of single-centre trials. While the results are encouraging, we await multi-centre randomized trials and cost-effectiveness studies before recommending routine use locally.

7. The evaluation of patients with stents and CABGs has limitations, but may be appropriate in select scenarios.

8. Stenosis severity should be reported in defined ranges rather than assigning a specific percentage, and comment should be made on the type of plaque involved.

9. Radiation exposure should be kept to a minimum in line with the ALARA principle. Radiation dose-saving measures should be routinely employed where appropriate.

10. Expertise in the performance and interpretation of coronary CTA scans is very important.
INTRODUCTION

Coronary artery disease (CAD) remains a leading cause of death in western societies. In Australia, it affects nearly 640,000 people and accounts for 18% of all deaths.¹ The identification and appropriate investigation of patients with coronary artery disease are central components for subsequent treatment and improvements in the health of those patients. Despite the various biomarkers and functional tests available for risk stratification, for some patients we look for the reassurance of anatomical information on the coronary vasculature. This is usually done via coronary angiography, which remains the gold standard for luminal assessment but carries some risks due to its invasive nature. Furthermore, the proportion of patients who have normal coronary angiograms has remained relatively stable at 15%, with a higher proportion of normal studies in women.² ³

The ability to provide this anatomical information noninvasively would be an attractive and probably safer alternative to coronary angiography. Two technologies which have undergone evaluation for this purpose are multidetector computed tomography (MDCT) and magnetic resonance imaging (MRI). This document will review both modalities but the main focus will be on MDCT because the technology has improved tremendously in recent years to a stage where widespread availability and implementation are possible. A comprehensive review of other functional imaging modalities and risk stratification tools / biomarkers is beyond the scope of this document. The topic of coronary artery calcium scoring is dealt with in a different document from CSANZ.

MULTIDETECTOR COMPUTED TOMOGRAPHY (MDCT)

Technology

The challenges in imaging the coronary vessels were to overcome cardiac motion and be of sufficient quality to reliably detect a lesion. Initial CT technology involved fixed detectors in the form of ‘electron beam CT’ which provided very good temporal resolution (50 – 100 ms) but poor spatial resolution and long scan times (>20 s). They were used primarily for detection and quantification of coronary calcium,⁴ and it was not until the 1990s that the first coronary CT angiogram was described.⁵

The development of MDCT with increasing numbers of finer detectors and faster gantry rotation times has resulted in improved spatial and temporal resolution to provide satisfactory images of the coronaries during diastole when there is least motion (Table 1).
Table 1. Timeline and improvements in MDCT.

<table>
<thead>
<tr>
<th>Detectors</th>
<th>Year introduced</th>
<th>Temporal resolution</th>
<th>Detector width</th>
<th>Coverage (z-axis)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>1999</td>
<td>400 ms</td>
<td>1.0 – 1.5 mm</td>
<td>0.6 cm</td>
</tr>
<tr>
<td>16</td>
<td>2001</td>
<td>190 – 250 ms</td>
<td>0.5 – 0.75 mm</td>
<td>1.2 cm</td>
</tr>
<tr>
<td>64</td>
<td>2004</td>
<td>165 -200 ms</td>
<td>0.5 – 0.625 mm</td>
<td>2.9 - 4 cm</td>
</tr>
<tr>
<td>64 x 2 DSCT</td>
<td>2005</td>
<td>83 ms</td>
<td>0.6 mm</td>
<td>2.9 cm</td>
</tr>
<tr>
<td>256</td>
<td>2007</td>
<td>135 ms</td>
<td>0.625 mm</td>
<td>8 cm</td>
</tr>
<tr>
<td>320</td>
<td>2007</td>
<td>175 ms</td>
<td>0.5 mm</td>
<td>16 cm</td>
</tr>
<tr>
<td>128 x 2 DSCT</td>
<td>2008</td>
<td>75 ms</td>
<td>0.6 mm</td>
<td>4 cm*</td>
</tr>
</tbody>
</table>

DSCT denotes dual source CT. *Coverage of whole heart possible with high-pitch protocol

The majority of coronary CT angiograms performed today are done on 64-detector systems, which require a stable regular heart rate of <65 beats per minute, breath hold of <10 seconds and about 5 heart beats to image the entire heart. Due to these limitations, there may be potential artefacts introduced by motion, breathing, ectopic beats or arrhythmias. From the common platform of 64-detectors, the various manufacturers have adopted different pathways which improve on the variables of resolution, speed, coverage or a combination of these.

Resolution

The spatial resolution of a CT system is largely limited by the detector width. An axial CT image is made up of three dimensional voxels which have an in-plane resolution (x and y – axis) and usually worse through-plane (z-axis) resolution. The shape of this voxel is therefore a rectangular block rather than a perfect cube. This can be a limitation when performing certain image manipulations or reformats as there will be some interpolation of data. This issue is becoming less evident in modern 64-detector systems. Some manufacturers have produced an isotropic or cubic voxel from the outset (e.g. Toshiba – 0.5 x 0.5 x 0.5 mm) while others have adopted a multi-sampling approach. Using a flying focal spot in the z-axis, it is possible to improve on the spatial resolution; e.g. a detector width of 0.6mm may result in an isotropic resolution of 0.33mm from oversampling (Somatom Definition AS, Siemens Medical, Germany).

Recently, one manufacturer has introduced a high-definition scanner with an in-plane spatial resolution of 0.23mm with 64-detectors (Discovery CT750 HD, GE Healthcare, USA). This is approaching the spatial resolution of invasive coronary angiography, which is 0.20 – 0.25mm. Utilizing a novel statistical iterative reconstruction algorithm (ASIR), Min and colleagues were able to demonstrate better visualization of coronary stents and greater intraluminal stent area compared with conventional CT systems.\(^6\)
**Speed**

Apart from trying to decrease gantry rotation times, a breakthrough in improving true temporal resolution occurred with the introduction of dual source CT (DSCT). This technology involved two sets of tubes and detectors placed 90 degrees apart in the gantry to obtain images with only a quarter rotation. This has resulted in good image quality at higher heart rates\(^7,8\) and even in atrial fibrillation.\(^9\)

Towards the end of 2008, the second generation DSCT scanner was introduced with two sets of 128-detectors capable of even faster gantry rotation and ultra-high pitch (Definition Flash, Siemens Medical, Germany). The two set of detectors are imaging mostly different areas of the heart as the gantry rotates. This has enabled both speed and coverage of the whole heart in 250ms and within one heart beat.\(^10,11\)

Dual energy CT (DECT) usually involves the two tubes of a DSCT system emitting two different energies (e.g. 80kV and 140kV), resulting in different attenuation values from the absorption of energies by the objects in question.\(^12\) Each voxel or point in tissue will have two CT values (Hounsfield Units) and the analysis is conducted based on “three-material decomposition” of the resulting images. It has the ability to discriminate between iodine and calcium in phantom models and vasculature of cadavers.\(^13\) In future, this technology may allow more accurate assessment of coronary plaque and stenosis by better discrimination between bright contrast, calcium and other plaque components.

**Coverage**

In late 2007, manufacturers released 256 (Philips) and 320-detector systems that are capable of volumetric whole organ scans. Although the temporal resolution may be similar to 64-detector systems, the 320-detector (Aquilion ONE, Toshiba, Japan) is capable of imaging the whole heart in one heart beat thereby providing images free from step-artefacts.

**Radiation**

As coronary CT angiography is increasingly performed in different healthcare settings around the world, the issue of radiation exposure has become a major concern in recent times. An early study comparing 16 and 64 detector systems reported mean effective doses of 10mSv and 15mSv respectively, when no dose-saving measures were employed.\(^14\) Radiation exposure is generally higher for women (10 – 21mSv) compared to men (7 – 15mSv), largely due to breast tissue.\(^15\)

A simple strategy to limit radiation is to scan only the organ of interest rather than from the carina to below diaphragm. An increase in scan length of 1cm can lead to a 5% increase in the radiation.\(^16\) In helical or retrospectively triggered scanning, x-rays are emitted throughout the cardiac cycle. Every manufacturer provides ECG-gated dose modulation, which decreases the tube current by up to 80% during systole, and only provides full current during the brief diastolic period of interest. This method has been shown to reduce radiation by 25-40%.\(^14,16,18\)
X-ray exposure changes in a linear fashion with tube current (mA) but with the square of the tube voltage (kV). Therefore, a reduction from 120kV to 100kV in small to moderate body masses (e.g. <85 kg) could result in a radiation exposure drop of 46 – 64%. Recently, non-helical scanning, where the exposure is prospectively triggered to occur only in diastole (“step-and-shoot”) has resulted in reductions in radiation of about 80% without compromising diagnostic quality. Patients need to have low heart rates (<60 bpm) and a stable rhythm without ectopics or much heart rate variability. While the radiation exposure will vary depending on whether temporal “padding” is employed, effective doses for prospective scanning are around 2-3mSv for modern 64-detector systems and <1mSv is achievable with second generation DSCT. 

The PROTECTION I study was an international multi-vendor observational study into radiation exposure involving nearly 2,000 patients from 21 university and 29 community hospitals. The vast majority (96%) were studied using 64-detector scanners but there was a wide range of effective doses across different manufacturers (median 9 – 19mSv) as well as across different sites using machines from the same manufacturer. ECG-gated dose modulation was applied in 38% of patients but only 5% had tube voltage reduction (100kV) and 6% employed prospective scanning. In a recent sub-analysis, prospective scanning incurred much less radiation compared to retrospective scanning (3.6 v 11.2 mSv) without impairing diagnostic image quality.

In a recent multi-centre trial of nearly 5,000 patients, implementation of dose reduction techniques resulted in a 53% decrease in radiation exposure from a median of 21mSv to 10mSv without deterioration in diagnostic quality. The intervention involved education of a physician and radiographer at each participating site and implementation of adequate patient preparation, use of beta-blockers and nitrates, limiting scan length, ECG-gated dose modulation and using 100kV tube voltage when appropriate. The most significant change was use of 100kV, and the greatest improvements were made by smaller community hospitals.

We recommend adopting the following strategies for reducing radiation where appropriate:

1. Limiting the scan volume to the organ of interest
2. Prospectively triggered scanning.
3. ECG-gated dose modulation
4. Reducing tube voltage to 100kV in smaller patients (<85kg; BMI <30)
Diagnostic Accuracy

Comparisons between 16 and 64 detector systems have reported superior performance of 64-MDCT.\textsuperscript{25-27} Many studies involving 16-MDCT excluded vessels <1.5 mm from analysis. There is a tendency to overestimate lesion severity, especially in calcific plaques due to blooming artefact.\textsuperscript{28} Despite the improvements of 64-MDCT, the image quality of segments >2.0 mm remains better than those <2.0 mm,\textsuperscript{29} and proximal better than distal.\textsuperscript{30,31}

Since the introduction of 64-detector systems, numerous single-centre studies comparing the accuracy of coronary CTA with traditional coronary angiography for significant stenoses have been published. Most had less than 100 patients and used a binary cut-off of 50% stenosis in their analyses. Meta-analyses of these studies have been performed (Table 2).

**Table 2.** Meta-analyses of native coronary arteries studied with 64-MDCT.

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Analysis reporting</th>
<th>Sensitivity</th>
<th>Specificity</th>
<th>PPV</th>
<th>NPV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abdulla\textsuperscript{32}</td>
<td>2007</td>
<td>Patients 1251</td>
<td>98%</td>
<td>91%</td>
<td>93%</td>
<td>97%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Segments 18920</td>
<td>86%</td>
<td>96%</td>
<td>83%</td>
<td>97%</td>
</tr>
<tr>
<td>Mowatt\textsuperscript{15}</td>
<td>2008</td>
<td>Patients 1286</td>
<td>99%</td>
<td>89%</td>
<td>93%</td>
<td>100%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Segments 14199</td>
<td>90%</td>
<td>97%</td>
<td>76%</td>
<td>99%</td>
</tr>
<tr>
<td>Stein\textsuperscript{30}</td>
<td>2008</td>
<td>Patients 2045</td>
<td>98%</td>
<td>88%</td>
<td>93%</td>
<td>96%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Segments 27099</td>
<td>90%</td>
<td>96%</td>
<td>73%</td>
<td>99%</td>
</tr>
</tbody>
</table>

PPV denotes positive predictive value; NPV, negative predictive value.

From these pooled results, it is clear that coronary CTA has excellent negative predictive value but somewhat variable positive predictive value. Therein lies its strength as a tool to rule out significant CAD. The lower sensitivity and higher specificity of the analyses by segment are expected because patients are defined as having CAD if any segments are positive for significant disease. The percentage of non-evaluable segments range from 4 to 8%. The left main coronary artery has the best sensitivity (91-100%) and specificity (100%) while the mid-right coronary has the worst (81% and 95%, respectively).\textsuperscript{30,31}

The prevalence of CAD in these meta-analyses was high, around 60%, which impacts the predictive values. Meijboom et al. studied the accuracy of 64-MDCT in symptomatic patients with low (13%), medium (53%) and high (87%) estimated pre-test probability of CAD, and found 100% NPV in the low-to-intermediate group but 89% in the high group.\textsuperscript{33}

In recent times, results from multi-centre and sometimes multi-vendor validation trials of 64-MDCT have been published (Table 3). The CORE64 trial was a highly anticipated single vendor, international multi-centre trial of 291 patients comparing 64-MDCT to conventional angiography.\textsuperscript{34} The authors reported almost 100% of segments were evaluable but excluded patients with high calcium scores (>600) and vessels <1.5 mm. The poor NPV of 83% was attributed to the high prevalence of CAD (56%) in the study population. Although the study
found that MDCT could accurately identify the presence of significant CAD and those requiring subsequent revascularization, the authors concluded that coronary CTA with the 64-MDCT technology examined could not replace conventional coronary angiography.

**Table 3.** Prospective multi-centre validation trials of 64-MDCT

<table>
<thead>
<tr>
<th>Author</th>
<th>Year</th>
<th>Analysis reporting</th>
<th>Sensitivity</th>
<th>Specificity</th>
<th>PPV</th>
<th>NPV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Miller</td>
<td>2008</td>
<td>Patients 291</td>
<td>85%</td>
<td>90%</td>
<td>91%</td>
<td>83%</td>
</tr>
<tr>
<td>Meijboom</td>
<td>2008</td>
<td>Patients 360</td>
<td>99%</td>
<td>64%</td>
<td>86%</td>
<td>97%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Segments 5297</td>
<td>88%</td>
<td>90%</td>
<td>47%</td>
<td>99%</td>
</tr>
<tr>
<td>Budoff</td>
<td>2008</td>
<td>Stenosis &gt;50%</td>
<td>95%</td>
<td>83%</td>
<td>64%</td>
<td>99%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stenosis &gt;70%</td>
<td>94%</td>
<td>83%</td>
<td>48%</td>
<td>99%</td>
</tr>
</tbody>
</table>

PPV denotes positive predictive value; NPV, negative predictive value.

At the end of 2008, Meijboom et al. reported the results of a multi-centre, multi-vendor trial of 64-MDCT.35 Their specificity and PPV were much lower than other studies, which may in part be due to inclusion of all segments regardless of image quality. This is closer to the real world situation in which a non-evaluable segment or stenosis >50% will probably result in an invasive angiogram. Another factor could be the high pre-test probability of disease in their population.

The ACCURACY trial by Budoff et al. was somewhat different in that they studied 230 symptomatic low (25%) CAD prevalence patients scheduled to have coronary angiograms and provided analysis by stenosis >70% in addition to the usual >50% cut-off.36 They included patients with heart rates >65bpm, high calcium scores and obesity. They showed that NPV remained high and specificity is comparable to other noninvasive stress imaging tests at both cut-offs.

The high negative predictive value of coronary CTA has received further support with a study showing freedom from significant cardiac events for 18 months if the coronary CTA was normal.37 This study of 1,256 patients who were followed for up to 2 years looked at composite endpoints of death, AMI or hospitalization due to unstable angina in a population with very low event rates. They also found that coronary CTA provided additional prognostic value to the Framingham Risk Scores (FRS), with non-obstructive CAD having a lower event rate and obstructive CAD having a higher event rate than predicted by the FRS alone. Another study of 436 symptomatic patients reported that those patients with minimal or no CAD on coronary CTA were free from events at 3 years of follow-up: a NPV of 100%.38 The prevalence of CAD was 14% and they estimated significant cost savings (USD 15,300/patient) compared to conventional angiograms in their local healthcare system.

**Cost-effectiveness**

In Australia, there has been one study on behalf of the Medical Services Advisory Committee (MSAC) into the cost-effectiveness of coronary CTA for symptomatic patients who were otherwise referred for invasive coronary angiography.39 They used a cost-utility analysis and the outcome was given as incremental cost per quality of adjusted life year gained (QALY). Using a total procedure cost of $3,035 for an invasive coronary angiogram and $1,020 for a
coronary CTA, MSAC concluded that coronary CTA is a cost-effective strategy offering a higher health-related quality of life for symptomatic patients with up to 65% pre-test risk of CAD.

Quantitative assessment of stenosis

Most of the literature so far has used the binary cut-off of 50% stenosis in validating MDCT against coronary angiogram. In clinical practice and with invasive coronary angiography, further quantification of lesion severity is desirable to decide whether revascularisation is indicated. A few studies have compared stenosis severity on coronary CTA with quantitative coronary angiography (QCA) and intravascular ultrasound (IVUS).\textsuperscript{34, 36, 40-43} Although the correlations were good, there were large standard deviations (up to ±25%) in quantifying stenoses with current 64-MDCT systems.

Based on these studies, the Society of Cardiovascular Computed Tomography (SCCT) has published guidelines on the interpretation and reporting of coronary CTA, recommending that stenoses be graded in broad ranges rather than assigning a specific number (Table 4).\textsuperscript{44}

\textbf{Table 4.} Recommended stenosis grading

<table>
<thead>
<tr>
<th>Grade</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal</td>
<td>Absence of plaque and no stenosis</td>
</tr>
<tr>
<td>Minimal</td>
<td>&lt;25% stenosis</td>
</tr>
<tr>
<td>Mild</td>
<td>25% – 49% stenosis</td>
</tr>
<tr>
<td>Moderate</td>
<td>50% - 69%</td>
</tr>
<tr>
<td>Severe</td>
<td>70% - 99%</td>
</tr>
<tr>
<td>Occluded</td>
<td>100%</td>
</tr>
</tbody>
</table>

Although MDCT has the potential to characterize plaque composition, there is much overlap in CT values (HU) in the various types of non-calcified plaques (e.g. lipidic or fibrous).\textsuperscript{43, 45} The SCCT has recommended that plaques be described as “calcific,” “non-calcific” or “mixed.”\textsuperscript{44}

\textbf{Recommendations}

- Coronary CTA should be performed on systems with $\geq$64-detectors;
- Coronary CTA is best-validated in low-intermediate risk groups with symptoms;
- MDCT has a high negative predictive value and can rule out significant CAD in the appropriate population;
- Limitations of MDCT do not allow stenosis quantification in the same manner as invasive coronary angiography. Coronary CTA reports should use stenosis grading as recommended in Table 4, along with comments on the type of plaque;
- Lesions which are >50% on MDCT should be verified by another modality.
CURRENT CLINICAL INDICATIONS

We have discussed the role of MDCT as a tool to rule out significant disease in patients with suspected CAD and stable symptoms. There are other specific clinical scenarios which may warrant its use. In 2006, a multi-society group including the American Colleges of Cardiology and Radiology, American Heart Association and other expert groups published guidelines on appropriateness criteria for both MDCT and MRI for cardiac applications. Below is a summary of the MDCT indications at that time:

**Table 5. Appropriate indications**

<table>
<thead>
<tr>
<th></th>
<th>Evaluation of chest pain - intermediate pre-test probability of CAD</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>• Unable to exercise or ECG uninterpretable</td>
</tr>
<tr>
<td>1</td>
<td>Evaluation of chest pain – uninterpretable or equivocal stress test / imaging.</td>
</tr>
<tr>
<td>2</td>
<td>Evaluation of acute chest pain (ED)</td>
</tr>
<tr>
<td></td>
<td>• Intermediate pre-test probability</td>
</tr>
<tr>
<td></td>
<td>• No ECG changes and normal cardiac enzymes</td>
</tr>
<tr>
<td>3</td>
<td>Evaluation of suspected coronary anomalies</td>
</tr>
<tr>
<td>4</td>
<td>Evaluation of CAD in new onset heart failure</td>
</tr>
<tr>
<td>5</td>
<td>Assessment of complex congenital heart disease</td>
</tr>
<tr>
<td></td>
<td>• Coronary &amp; great vessel anomalies</td>
</tr>
<tr>
<td></td>
<td>• Cardiac chamber &amp; valves</td>
</tr>
<tr>
<td>6</td>
<td>Evaluation of pulmonary vein anatomy prior to radiofrequency ablation for AF</td>
</tr>
<tr>
<td>7</td>
<td>Coronary vein mapping prior to placement of biventricular pacemaker</td>
</tr>
<tr>
<td>8</td>
<td>Repeat CABG – internal mammary and coronary artery mapping</td>
</tr>
<tr>
<td>9</td>
<td>Technically difficult or limited images from echocardiogram or MRI</td>
</tr>
<tr>
<td></td>
<td>• Evaluation of cardiac mass (tumour or thrombus)</td>
</tr>
<tr>
<td></td>
<td>• Evaluation of pericardial conditions (mass, pericarditis, post cardiac surgery)</td>
</tr>
</tbody>
</table>

There are similar tables in the 2006 guidelines for inappropriate and uncertain indications. Indications deemed inappropriate generally involved:

- asymptomatic patients;
- high pre-test probability of CAD (including positive stress test / imaging);
- positive cardiac enzymes or ST elevation on ECG.

Since the 2006 guidelines were published, there have been several publications addressing additional indications for coronary CTA, and the multi-society group responsible for the 2006 guidelines released an updated expert consensus document on coronary CTA in May, 2010. The additional indications for coronary CTA now supported are:

- Pre-operative assessment to rule out significant CAD prior to non-coronary cardiac surgery. The prevalence of CAD in the 70 patients evaluated was 26%. The authors reported sensitivity was 100%, specificity 92%, PPV 82% and NPV 100%. The excellent NPV would have permitted the 69% of patients in the study with a negative
CTA to avoid invasive angiography. A history of angina was unreliable in predicting significant CAD. The subset of patients with aortic stenosis had higher coronary calcification, which led to an overestimation of stenosis (PPV 75%) but the excellent NPV of 100% was preserved.

- Detection of CAD in patients with left bundle branch block. Stress testing / imaging may be difficult in this population. Invasive coronary angiography showed significant CAD in 44% of this group, with MDCT having a PPV of 91% and NPV 97%.

- Ruling out significant CAD in patients with dilated cardiomyopathy. This study utilizing 16-MDCT in 61 patients with dilated cardiomyopathy of unknown aetiology was able rule out significant CAD with sensitivity 99%, specificity 96%, PPV 82% and NPV 99.8%. This indication is similar to the investigation of new onset heart failure, as outlined in Table 5.

- Alternative to invasive coronary angiography to detect CAD in the follow-up of patients following cardiac transplantation. Two small single-centre studies have examined this issue. The sensitivity for detecting either coronary stenosis or plaque when compared with the combination of invasive angiography plus IVUS was 70% with specificity 92%.

**Recommendations**

- Patients with indications as outlined in Table 5 are appropriate for evaluation with MDCT.
- Coronary CTA should not be performed in patients who have a high pre-test probability of CAD or are known to have significant CAD or acute coronary syndrome.
- Coronary CTA is appropriate in the investigation of patients with cardiomyopathy of unknown aetiology and patients with left bundle branch block.
- Coronary CTA is appropriate to rule out CAD in patients scheduled for non-coronary cardiac surgery. The CTA finding of a stenosis >50% or highly calcified plaque that precludes accurate assessment of stenosis severity will necessitate invasive angiography.
- Coronary CTA may be an appropriate alternative to invasive angiography in the routine follow up of patients after cardiac transplantation, although confirmation in larger studies is desirable.

In addition, the following potential applications of coronary CTA were addressed in the 2010 Expert Consensus document, but the recommendations to be made on these issues are less clear at present or there is insufficient data to provide a consensus opinion:

**Evaluation of Acute Chest Pain in the Emergency Department**

The problem of acute chest pain in the emergency department (ED) can be taxing, not only on the staff but on the time and resources of the hospital system. More than 60% of chest pain presentations to ED in the USA are found not to have acute coronary syndrome, but physicians are reluctant to discharge patients because there is a reported 2% rate of missed AMI. Based on the ability of coronary CTA to rule out significant CAD in patients with stable symptoms, there have been a number of studies evaluating its use in acute chest pain. All were conducted in patients with initial negative cardiac enzymes and no ischaemic ECG changes.

An early prospective blinded study by Hoffmann et al. included coronary CTA on 103 patients at admission to rule out ACS. The absence of significant stenosis accurately
predicted the absence of ACS (NPV 100%). On the other hand, the PPV was only 47%, indicating a large number of false positives. In a subsequent study (ROMICAT), the authors screened 1,869 patients but only enrolled 368 (20%). About 50% of these patients had a negative coronary CTA, with a NPV of 100% for ACS but poor PPV. For patients with a low-to-intermediate pre-test probability of ACS, MDCT may be a useful triage tool in ED.

Similarly, another study of 58 patients found that of the 60% of patients with a negative coronary CTA, none had AMI or death after discharge after 15 months follow-up. The authors reported an excellent NPV of 97% and poor PPV of 52%.

Goldstein and colleagues conducted a single-centre randomized trial of MDCT for ED chest pain versus the usual management, which was a nuclear stress test. MDCT patients with non-significant lesions were discharged, those with a severe (>70%) stenosis underwent invasive coronary angiography, and those with a moderate stenosis underwent stress testing. MDCT immediately triaged 75% of patients to discharge or invasive coronary angiography, with the remainder undergoing stress testing. Patients were followed-up for 6 months, and both the MDCT and the usual nuclear stress pathways were found to be 100% safe. Compared to the usual standard of care, the MDCT strategy saved time (3.4 v 15 hours), costs ($1,586 v $1,872) and resulted in fewer repeat evaluations for recurrent chest pains (2% v 7%).

In a prospective study of 85 patients with chest pain in the ED, all underwent MDCT and nuclear stress imaging to determine accuracy in excluding significant CAD and events at 30 days. Both MDCT and nuclear imaging had high NPVs (99% and 97%, respectively) but poor PPVs (50% and 38%, respectively). The accuracy of MDCT was similar to nuclear stress imaging in this low-risk cohort.

In Australia, there has been a recent publication utilizing DSCT in the evaluation of acute chest pain in 89 patients. It was a prospective observational study with follow-up to 1 year. The result of the coronary CTA was not given to the treating team, and all patients underwent subsequent stress testing and standard care. Coronary CTA identified all patients with a severe stenosis requiring invasive coronary angiography. It identified 3 of 4 patients with a subsequent positive troponin. None of the patients died or had AMI in the follow-up period.

The ‘Triple Rule-Out’ CT Scan
MDCT already has proven clinical accuracy for the diagnoses of aortic dissection and pulmonary embolism, while coronary CTA studies for acute chest pain have been promising. The idea of a ‘triple rule-out’ scan protocol to exclude all three potentially fatal conditions has been proposed. There are technical limitations to the protocol, involving rapid scanning of the entire chest, streak artefact from the right heart, optimal timing of the contrast bolus and extra radiation (up to 50%). The optimal scanning protocol for each target of the scan is compromised by targeting all three issues simultaneously. A feasibility study of 50 patients with atypical chest pain using a novel protocol with 64-MDCT yielded good-quality images but 8 patients were excluded from coronary analysis due to artefacts. A recent study of 31 patients using the new second generation DSCT to perform the triple rule-out protocol resulted in only 4.1mSv of radiation compared with 20mSv using conventional MDCT, although only 85% of coronary segments were diagnostic versus 93% with conventional MDCT.

Recommendations:
• Use of coronary CTA in the evaluation of acute chest pain is feasible and shows promise, but more data from multi-centre randomized trials on outcomes are needed before routine use is recommended.

• It should be performed in low-to-intermediate risk patients without ECG changes or positive cardiac enzymes. Algorithms for integrating MDCT into chest pain evaluation pathways may need to be tailored for local facilitation of workflow.

• Preliminary data on time saved and cost-effectiveness in the USA are encouraging but this needs to be studied locally.

• Currently, we cannot recommend adopting a ‘triple rule-out’ strategy for use of MDCT in the evaluation of acute chest pain.

Coronary stent imaging
Evaluation of in-stent restenosis (ISR) has always been challenging due to metal artefacts, partial volume effects and beam hardening, with a high percentage of unevaluable stents in the past. Improvements with 64-MDCT and DSCT have decreased the proportion of unevaluable stents to 12%. Stent diameter of <3.0 mm has been identified as a major predictor of an unevaluable stent. The mean sensitivities (91%) and specificities (94%) were high and the NPV (98%) was excellent, but the PPV (63%) was poor. A sub-study of the multi-centre CORE 64 trial was recently published, which found evaluability also decreased with thicker stent struts. About 80% of stents in that study were <3.0mm diameter and only 64% were evaluable, with poor PPV (57%) and NPV (80%). An early study evaluating ISR in left main stents (post-dilated diameter 4.0mm) found the overall accuracy for simple left main stents was 98% but for complex bifurcation stents, it was 83%. Recent technological advancements in spatial resolution with so-called ‘high definition’ MDCT show promise, with better intra-luminal stent quantification.

Recommendations:
• Routine use of MDCT to evaluate in-stent restenosis cannot be recommended currently, but this situation is likely to change with evolving technology.

• Assessment of stents is currently feasible in the setting of stent diameters >3.0mm and in simple left main stents.

Coronary Artery Bypass Grafts
The assessment of CABGs has always been much easier than native coronary arteries due to their relatively larger size and immobility. Even with 4-detector and 16-detector systems, the image quality was good, but the evaluation of distal anastamose and native vessels has been challenging. With 64-MDCT, 100% of grafts were evaluable with excellent NPV (100%) and PPV (92%). However, the native coronaries are often extremely diseased and calcified, particularly in the smaller distal vessels beyond the graft anastomoses, resulting in a high NPV (96%) but low PPV (44%).

Consequently, the multi-society guidelines published in 2006 rated the use of MDCT in CABGs and native coronary arteries as ‘uncertain,’ with a borderline score for appropriateness. The new 2010 guidelines are similarly equivocal, noting the excellent accuracy for graft assessment but the limitations of assessing the anastomoses and native vessels.
Recommendations:

- Use of MDCT in patients with CABGs can only be recommended to assess graft patency. Assessment of the native coronaries can be challenging currently but may improve with improvements in technology.
- It may also be used when invasive angiography fails to demonstrate a graft or adequately assess its patency.
- It is appropriate to use MDCT for surgical planning of repeat CABG to map internal mammary arteries, grafts and native coronary arteries.

Chronic Total Occlusions

Percutaneous coronary intervention (PCI) for chronic total occlusions (CTO) can be a most difficult challenge involving excessive time, contrast and radiation. Success rates are poor due to failure to cross the lesion with guide-wires. The operator sometimes does not know the length of the occlusion, the course of the occluded vessel or the extent of calcification. It was not appreciated until recent years that MDCT could visualize segments of vessel beyond occlusion sites due to collateral filling with contrast. Mollet et al. found occlusion length, a blunt stump and calcification to be predictors of PCI procedural failure. Similarly, an Australian study found heavy transluminal calcification on MDCT to be an independent predictor of procedural failure.

More recently, a larger study of 142 CTOs found severe calcification, length of calcification and calcification at the entry point of the occlusion to be factors in procedural failure. The authors found that the mean effective radiation dose for PCI was 39mSv and for coronary CTA was 22 mSv, and questioned if the extra radiation was warranted. However, with current dose-reduction strategies, radiation doses for prospective coronary CTA could be as low as 2-3 mSv.

There are no trials to date comparing the efficacy of a pre-PCI coronary CTA to routine care in CTO intervention. One assumes the information derived from a pre-PCI coronary CTA may change interventional strategies in terms of employing different guide-wires and approaches, or may result in a decision not to attempt the procedure.

Recommendations:

- The use of MDCT to assess CTO may be useful in planning PCI of the lesion.
- Extensive calcification, especially at the entry site, and length of occlusion may predict procedural failure.

Coronary CTA in Asymptomatic Individuals

The 2010 Consensus statement - acknowledges the high prevalence of early stage atherosclerosis in young asymptomatic adults and the limitations of current clinical risk assessment tools, including the Framingham risk score. It cites recent evidence that coronary calcium scoring may improve risk stratification provided by the Framingham risk score. It notes that while coronary CTA can additionally image non-calcified plaque, there is currently a lack of evidence linking non-calcified plaques that are non-obstructive with an independent increase in risk. Moreover, asymptomatic patients without coronary calcification have a very low event rate, around 0.1% per year. There are also no published trials demonstrating improved outcomes after specific therapy in asymptomatic subjects with non-calcified coronary plaque on CTA. Nevertheless, the Consensus document does provide an extensive
review of the emerging CTA research on coronary plaque characterisation, the assessment of atherosclerotic burden, the natural history of plaque progression and its response to treatment, and the identification of vulnerable plaque. This research work does not yet provide a basis for recommending coronary CTA in asymptomatic subjects. As this research work progresses and with further technological improvements, it will become clearer whether coronary CTA will have a future role in asymptomatic subjects to aid individualisation of risk and/or response to treatment.

**TRAINING & ACCREDITATION**

Performance and reporting of cardiac CT requires competency in many areas. Practitioners should have a good understanding of technical aspects of CT, cardiac anatomy and pathology, as well as being able to identify extra-cardiac pathology which may occur in the field of view of a cardiac CT.

In 2009, the Australian New Zealand Conjoint Committee for the Recognition of Training in CT Coronary Angiography issued guidelines which exceed those of the ACC/AHA (www.anzctca.org). In summary, they recommended the following:

1. **Level A – for independent supervision and reporting of cardiac CT.**
   (i) Specialist in Cardiology, Radiology or Nuclear Medicine.
   (ii) Coursework – 40 hours, with at least 20 hours of interactive ‘hands on’ training under the supervision of a Level B (mentor level) specialist.
   (iii) Logbook of 150 cases verified by a Level B specialist. The 150 cases must include a minimum of 50 live cases (no more than 25 of the live cases can be achieved during a training course), 50 cases correlated with another imaging modality and/or appropriate clinical follow-up, 25 cases with non-coronary cardiac findings and 25 cases with non-cardiac findings. Live cases claimed outside a course must include the name of the claimant in the patient’s report.

2. **Level A – recertification.**
   (i) Evaluation of 300 cases within a 3-year period recorded in a logbook.
   (ii) 30 cases correlated (as defined above).
   (iii) Maximum of 100 cases may be achieved via courses or library cases.

Logbooks will be subjected to random audits. For recertification purposes, live cases can be claimed by no more than two doctors, and only if each reporting doctor’s name appears on the patient’s report. The criteria for accreditation and recertification of a Level B (mentor level) specialist are more onerous, but essentially require a doubling of the Level A caseload requirements (www.anzctca.org).

Accreditation and training on the international front has largely been developed by organizations in USA. In 2005, the ACC/AHA along with other professional societies published guidelines on clinical competence in cardiac CT and cardiac MRI. These guidelines have been informally adopted by the European Society of Cardiology. One can apply to the SCCT for verification of one’s cardiac CT experience. The SCCT has also issued guidelines on performance and reporting of cardiac CT. In 2008, board examinations were introduced by the Certification Board of Cardiovascular Computed Tomography for USA.
MAGNETIC RESONANCE IMAGING

MRI is a unique technology which allows noninvasive visualization of cardiovascular anatomy without ionizing radiation. However, there are some limitations, including long imaging time, the confined space in the scanner and the fact that MRI is contra-indicated in patients with certain metallic implants. MRI has the potential to provide information on cardiac anatomy, function (myocardial and valvular), perfusion and metabolism.

It has been almost 20 years since initial reports of MRI’s ability to image the coronaries with breath-holds of up to 18s. Often no exogenous contrast is needed for coronary MRA. Using bright-blood imaging sequences, image quality was good and compared favourably with invasive coronary angiography, with PPV 85% and NPV 95%. However, the spatial resolution obtainable was approximately 1mm, and was not sufficient for routine clinical use. The development of MR ‘navigator echo’ allowed free breathing acquisition of coronary artery images over many minutes, reducing motion artefacts by analysing data when the diaphragm or heart were in a small range of positions. With the advent of black-blood imaging and improvement in spatial resolution to 0.46 mm, visualization of the vessel wall in addition to the lumen was possible. A direct comparison of bright-blood and black-blood techniques was made in a small trial. There was no clear advantage to either technique but black-blood scans can be difficult to interpret because calcification and motion artefacts may lead to signal attenuation.

The ability of MRI to evaluate CABGs has also been reported. Flow through bypass grafts was able to be measured, and when incorporated with MRI images, yielded high sensitivity (96%) and specificity (92%) in detecting obstructive stenoses >70%. However, only 80% of grafts could be scanned successfully.

A landmark multi-centre study compared MRI to invasive coronary angiography in 109 patients using a volume-targeted coronary MRA protocol. This technique is operator-dependent, requiring accurate localization of the coronary arteries and only limited access to the distal vessels and branches. The authors reported an overall accuracy of 72% in diagnosing significant CAD but 16% of coronary segments were not evaluable. All patients with left main or triple vessel disease were correctly identified by MRA.

With the advent of parallel imaging and steady-state free precession (SSFP), “whole heart MRA” with a single breath-hold became feasible. This technique was less operator-dependent, and was found to have an improved overall accuracy of 89% when compared with invasive angiography. A recent study comparing whole heart MRA to volume-targeted MRA using exogenous contrast found more visible segments and side branches with the whole heart MRA technique. Typical spatial resolutions achievable with the whole heart technique are 0.7-0.8 mm in plane and 1-3mm through plane.

Initial reports of imaging coronary arteries using high field 3T systems have been reported. Compared with traditional 1.5T systems, 3T can offer twice the signal-to-noise ratio, which can theoretically result in a four-fold reduction in scanning time. However, one problem with 3T scans can be reliable R-wave triggering, which may be overcome with sophisticated algorithms or T-wave triggering instead.

Despite these improvements in MRI technology, coronary MRA has not seen widespread clinical use. This is due, in part, to limited expert centres and limited access to MR systems. However, the main factor currently is the competition MRI faces from MDCT, which offers...
superior spatial resolution, speed, diagnostic accuracy and widespread availability. The 2006 multi-society appropriateness criteria pertaining to coronary MRA recommends its use in:

1. Evaluation of suspected coronary anomalies
   The 2008 AHA committee on imaging recommends that MRA is preferred to MDCT due to radiation concerns.

2. Assessment of complex congenital heart disease, including anomalies of coronary circulation, great vessels, cardiac chambers and valves.

The guidelines state it is ‘inappropriate’ to use coronary MRA to evaluate symptomatic patients with intermediate pre-test probability of CAD, which contrasts with their recommendation for MDCT in the same group of patients. It was also deemed ‘inappropriate’ to use coronary MRA to evaluate CABGs in patients with symptoms.

Recommendations:
- Coronary MRA may be used to evaluate suspected coronary anomalies or in complex congenital heart disease.
- Perhaps in a very select population where radiation is a concern (e.g. young women), coronary MRA may be used to exclude significant CAD in the proximal to mid-vessel level when performed in expert centres.

SUMMARY

Noninvasive coronary imaging, and MDCT in particular, has advanced significantly since the last guidelines were published. Rapid development of technology accompanied by an explosion in research into MDCT have provided us with a clearer picture of its strengths and weaknesses. The appropriate indications have expanded, and a marked reduction in radiation exposure has fuelled a rush to adopt this new imaging modality. It is important that this emerging technology not be misused, and that consideration be given to other options when appropriate. Adequate training and accreditation is key to maintaining a high standard of the scans performed.
REFERENCES


