
Coronary computed tomography angiography: a new wave of cardiac imaging
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Abstract
Coronary computed tomography angiography (CTA) is becoming a popular non-invasive imaging modality for coronary arteries. It has high sensitivity and specificity in the evaluation of coronary artery disease (CAD). Due to its high negative predictive value, the main clinical role of coronary CTA is in the exclusion of significant CAD in the low to intermediate pretest probability patients. In the emergency department, coronary CTA helps to fast-track the triage of acute chest pain patients. One of the major coronary CTA’s limitations is its false positive findings in the presence of heavily calcified lesions. With the advance of CT technology, the radiation dose of coronary CTA has been reduced significantly. At present, coronary CTA is still not indicated for screening asymptomatic patients.

Introduction
In many parts of the world, coronary computed tomography angiography (CTA) is fast becoming a popular cardiac imaging modality. In Australia, the acceptance of coronary CTA has increased since it became a Medicare rebate item from 1 July 2011. This was largely due to the effort of Conjoint Committee for Recognition of Training in CT coronary angiography consisting of representatives from Cardiac Society Australia and New Zealand, Royal Australian and New Zealand College of Radiologists, and Australian and New Zealand Association of Physicians in Nuclear Medicine. Nonetheless, many doctors are still uncertain about the indications and unaware of the limitations of coronary CTA. Some are concerned about its radiation dose in comparison with other imaging modalities. This review article aims to clarify all these issues.

CT technology and coronary CTA
Despite the advance of CT technology, coronary CTA is still quite challenging to perform in comparison with CTA of the peripheral vascular system. Coronary arteries are small and moving with each heartbeat. In order to image coronary arteries well, the CT scanner used in coronary CTA must have high spatial and temporal resolutions. The scan also needs to be gated to the cardiac cycle so that the axial images obtained at a particular point in time of the cardiac cycle can be retrieved and reconstructed in phase (Fig. 1). There are two modes of electrocardiography (ECG) gating: retrospective and prospective gating modes. A retrospective gated scan acquires images throughout the whole cardiac cycle, whereas a prospective gated scan only acquires images during a particular time in cardiac cycle, such as during the diastolic phase when the heart is least mobile.
Nowadays, coronary CTA is predominantly performed with a multi-detector row CT (MDCT) for its wide z-axis coverage, high spatial resolution (0.4–0.6 mm) and temporal resolution (330 ms per rotation). Electron beam CT has been phased out due to its suboptimal spatial resolution in comparison with MDCT. Most MDCT scanners used to perform coronary CTA have a minimum of 64 rows of detectors, with a spatial resolution of 0.4–0.6 mm.1 It normally takes about 5–8 heartbeats to scan from the cranial to caudal aspects of the heart. The ECG-gated scan images are then restacked to form the linear images of coronary arteries (Fig. 2). A wider z-axis coverage with 126, 256 and even 320 row MDCT has the advantage of scanning the whole heart in a shorter time period, hence there is lesser demand on breath-holding duration and lesser subjection to heart rate variability, such as atrial or ventricular ectopics. The wide-array 320 row MDCT allows

Figure 1 Coronary computed tomography angiography can be performed with (a) retrospective ECG gating or (b) prospective ECG gating. ECG, electrocardiography.

Figure 2 Curved multiplanar reconstruction (a), maximal intensity projection (b) of coronary computed tomography angiography correlate well with the finding of invasive coronary angiography (c) showing a severe stenosis in the mid-left anterior descending artery.
the whole heart to be scanned in a single or two heartbeats; it essentially eliminates the issue of misregistration artefacts as seen on MDCT with lesser row number of detectors in the event of ectopic heartbeat or heart rate variation (Fig. 3).

The temporal resolution of the MDCT is limited by the rotational speed of X-rays gantry. Current MDCT has a rotational speed of 330 ms per round. Further increment of rotational speed of X-rays gantry is limited by the gravitational force it generates. By virtue of half-scan reconstruction, that is the X-ray image of one side of the vessel is similar to the X-ray image of the half of the vessel, a virtual temporal resolution of 155 ms can be achieved. Although the heart beats faster than the rotational speed of MDCT during the systolic phase, it has a relatively static period during the diastolic phase. Hence, the diastole is the opportunistic window period for scanning the heart and its coronary arteries with less motion artefacts. The duration of diastolic phase can be prolonged with the use of beta-blockers or other atrioventricular (AV) nodal blocking agents, such as diltiazem or verapamil. The target heart rate normally aimed for in coronary CTA is 60 b.p.m. or below.3

Clinical indications for coronary CTA

The clinical indications for coronary CTA should be based on the diagnostic accuracy of coronary CTA. Most published data suggest that coronary CTA has high sensitivity and specificity, with high negative predictive value but moderately high positive predictive value.1 In segment-based analysis, Schroeder et al.’s meta-analysis showed that coronary CTA had sensitivity and negative predictive value of 89% and 98% respectively. In patient-based analysis, patient with at least one coronary segment >50% stenosis, the sensitivity and negative predictive value of coronary CTA were reported as 98% and 95% respectively. Its high sensitivity and negative predictive value make coronary CTA a very useful tool to exclude significant coronary artery disease (CAD), in most cases defined as at least a coronary stenosis >50%. Its positive predictive value is only moderately good in segment-based analysis (78%) due to the presence of false positive findings. False positive findings of coronary CTA are predominantly related to overestimation of lesion severity in the presence of calcified plaques.4–6 Calcified lesions appear worse on coronary CTA because of calcium blooming and beam hardening effects (Fig. 4). There is not much we can do to eliminate the calcium-related artefacts other than using a higher tube voltage and trying to slow down heartbeats even further during coronary CTA scanning. Motion artefacts can also be the source of false positive (Fig. 3).

Current Society of Cardiovascular Computed Tomography/American Heart Association/American College of Cardiology (SCCT/AHA/ACC) guidelines suggest that in the detection of CAD in symptomatic patients without known heart disease, coronary CTA is appropriate for intermediate pretest probability patients. It is also appropriate in the low pretest probability patients who cannot perform exercise stress test or with equivocal functional tests.7,8 A negative coronary CTA provides us a high level of confidence in excluding obstructive CAD and relieve the patients from other investigations. However, it should not be used in the high pretest or high risk profile patients as it is more likely than not going to show the presence of calcified and non-calcified plaques. In this patient group, it is not
appropriate to use coronary CTA to decide precisely how narrow the coronary lumen is in view of its limited spatial and temporal resolutions. Such patients would be better off having their coronary arteries assessed with the invasive coronary angiogram or functional tests.

In the setting of acute chest pain suspicious of acute coronary syndrome (ACS), both low and intermediate pretest probability patients are appropriate for coronary CTA. Coronary CTA can exclude significant obstructive CAD more rapidly than current acute chest pain management pathway which relies on serial cardiac biomarkers and ECGs.9–11 The cost of care using coronary CTA in the chest pain triage is lower than the conventional chest pain management without the use of coronary CTA (38% lower).11 In addition, a triple rule out of coronary obstruction, aortic dissection and pulmonary embolism can be performed within a single scan of cardiac CT. In patients with positive ECG changes or highly elevated serial troponin assays, they would be better off evaluated with the invasive coronary angiography (ICA) and not coronary CTA.

Post revascularisation, coronary CTA is fairly useful in evaluating the patency of coronary bypass grafts.7,8 Due to its relatively static nature, coronary bypass graft is easier to scan, and the image quality is often excellent (Fig. 5). The diagnostic accuracy of coronary CTA for bypass graft is very high, with sensitivity, specificity, and negative and positive predictive values all close to 100%.12,13 However, coronary CTA is less useful in the evaluation of coronary stents due to stent blooming artefacts. Coronary CTA of stents suffers from a significant high number of false positive findings.14 Currently, only stents of ≥3 mm in diameter are suitable for coronary CTA, such as left main artery stent or proximal coronary

Figure 4 Heavy calcification in the left anterior descending on coronary computed tomography angiography (a) results in a false positive finding in comparison with invasive coronary angiography (b).

Figure 5 Curved MPR of a patent LIMA graft to the LAD of patient with recurrent left shoulder pain post CABG (a). The 3D picture shows a patent LIMA graft and also a severe stenosis in the left subclavian artery proximal to the origin of the LIMA graft as the cause of left shoulder pain (b). CABG, coronary artery bypass graft; LAD, left anterior descending artery; LIMA, left internal mammary artery; MPR, multiplanar reconstruction.
segment stent (Fig. 6). In both coronary artery bypass graft and stented patients, the degree of CAD in the native vessels cannot be accurately assessed with coronary CTA. The referrers need to understand that coronary CTA may not provide them the answer to the cause of chest pain post revascularisation per se.

In recent years, coronary CTA is also increasingly used in the evaluation of patients with suspected dilated cardiomyopathy. A negative coronary CTA further confirms that the cause of dilated cardiomyopathy is not due to obstructive epicardial CAD.7,8

By its tomographic nature, coronary CTA is quite a unique imaging modality in comparison with the conventional ICA. Coronary CTA provides an excellent cross-sectional view of all cardiac structures and coronary arteries. Calcified and non-calcified plaques are appreciated much better on coronary CTA than the ICA. It also shows a superb 3D relationship between coronary arteries and other cardiac structure. Hence, coronary CTA is very useful in the characterisation of coronary anomaly, such as anomalous coronary artery. Coronary CTA helps delineate the proximal course of anomalous coronary artery to see if it runs between aorta and pulmonary artery. An interarterial anomalous coronary artery can be associated with sudden cardiac death as compared with retroaortic or prepulmonic anomalous coronary artery (Fig. 7).15

**Other clinical scenario potentially indicated for coronary CTA**

Not infrequently, we come across a situation where the outcome of a functional test does not match the patient’s clinical presentation. For example, patients with a good history of ischaemic sounding chest pain produce a negative functional test, or patients with atypical chest pain end up with a positive functional test. In both situations, further testing with coronary CTA may help clarify if patients require an ICA.

In the setting of acute chest pain, troponin assays are invariably used in the emergency department to investigate the cause of chest pain. Not infrequently, we come...
Screening

Despite its popularity in certain parts of the world, at present there is not enough evidence to support the use of coronary CTA to screen asymptomatic patients for significant CAD. A large study performed in Korea, screening 1000 middle-aged asymptomatic patients, yielded a low incidence of significant CAD (5%). In those with significant CAD detected on coronary CTA, currently there is no data to support any form of treatment for subclinical CAD. More often than not, coronary CTA in asymptomatic patients may show mild atherosclerosis in the coronary arteries (which naturally comes with age), and subsequently may pose more uncertainties and unnecessary anxiety to the patients. As it currently stands, coronary CTA is not a screening tool for CAD.\(^7,8\)

Medicare rebate for coronary CTA

Medicare Australia stipulates that coronary CTA must be performed on a minimum 64-slice CT (or equivalent) at an experienced centre serviced by recognised coronary CTA reporters accredited by the joint committee (Australia-New Zealand Conjoint Committee for the Recognition of Training in CT Coronary Angiography). Coronary CTA referral can only be made by a specialist or physician. Consistent with the guidelines published by SCCT/AHA, Medicare Australia stipulates that coronary CTA is only indicated in symptomatic patient suspicious of coronary ischaemia but with a low to intermediate risk profile and would have been considered for ICA. The other indication of coronary CTA is exclusion or characterisation of anomalous coronary artery or coronary fistula. In young patients going for non-coronary cardiac surgery, coronary CTA is also considered an appropriate indication for Medicare rebate. The Medicare rebate item number for coronary CTA is 57360 (http://www9.health.gov.au/mbs/fullDisplay.cfm?type=item&q=57360&qt=item&criteria=57360).

Limitations of coronary CTA

Despite its attractiveness as a form of non-invasive imaging modality, coronary CTA has several limitations. Due to its significant dependence on the regularity of heart rhythm, coronary CTA in patients with markedly irregular heart rhythm, such as atrial fibrillation or frequent premature complexes, may not produce a good image quality. It is more certainly so if coronary CTA is performed using MDCT scanners that require a few rotations to ‘stitch’ up cardiac images as compared with a single rotation acquisition with a wide-array 320 MDCT or the latest Siemens flash scanner with a fast table speed.

Coronary CTA performed at a high heart rate may also yield suboptimal image quality as motion artefacts can cause poor visualisation of coronary lumen, and hence inaccurate assessment of luminal stenosis. A genius way to improve the temporal resolution of MDCT has been the creation of dual source CT (DSCT) scanner. The availability of second X-ray source at 90 degrees to the other X-ray source means the x-gantry needs to spin only a quarter of a cycle to obtain a particular segment of the coronary artery. Virtually, the temporal resolution of the DSCT reaches 83 ms. Such a high temporal resolution allows coronary CTA to be performed at higher heart rates than 60 b.p.m. and preclude the need for routine beta-blocker. Nonetheless, most DSCT operators still find that the use of beta-blockers helps obtain the best image quality and reduce the radiation dose of DSCT.\(^18\)

As mentioned earlier, heavy calcification of coronary vessels is a common source of false positive findings. Coronary CTA is not that helpful in patients who are likely to have extensive calcification, such as elderly patients or patients with chronic renal failure. Cast aside the issue of calcification, coronary CTA itself often overestimates the severity of lesion in comparison to ICA. The spatial resolution of coronary CTA is in the order of about 0.4–0.6 mm as compared with 0.1–0.2 mm with conventional ICA.

As coronary CTA involves the use of iodine-based contrast, patients with renal impairment and contrast allergy are not suitable to have coronary CTA.

Radiation dose

A few years back, coronary CTA was a contentious imaging modality due to its radiation dose. In the early day, with 16-slice CT, the radiation dose was estimated to be about 15–20mSv. As the CT technology improves, coupled with the industrial efforts in reducing the radiation dose of coronary CTA, nowadays coronary CTA can be performed at a much lower radiation dose. The use of prospective ECG-gated scanning mode helps reduce the radiation dose from 15–20mSv to 3–5mSV, a sheer reduction of about 70–80%.\(^19,20\) Coronary CTA performed with a lower tube voltage from 120 kVp to 100 kVp in appropriate patients can also reduce the dose by 40–50%.\(^21\)
Even in retrospective gated scanning mode due to clinical needs, ECG-gated tube current modulation helps reduce the dose by about 25–40%. Later, with the introduction of Siemens flash DSCT scanner, coronary CTA can be performed with a radiation of about 1mSv in one heartbeat using a high table speed. For comparison, conventional ICA yields a radiation dose of about 5–8mSv, while nuclear perfusion study yields a radiation dose of 10–15mSv in total for both rest and stress components. Our background cosmic radiation gives us 2.0–2.5mSv per year living in Australia. In short, the effective dose of coronary CTA has come down quite substantially over the last 5 years.

Functional information of coronary CTA

CT myocardial perfusion study

Coronary CTA provides excellent anatomical information, such as luminal stenosis, plaque characteristics and coronary anatomy. However, it lacks functional information, such as coronary flow and physiology. Stress cardiac CT is now possible albeit at a research level. Stress cardiac CT can be performed in conjunction with coronary CTA using adenosine induced myocardial stress. So far, cardiac CT stress perfusion studies yield comparable results with nuclear myocardial perfusion imaging. Hence, it has the potential to become a one-stop investigation to obtain anatomical and functional information of CAD, and to reduce the incidence of false positive findings of coronary CTA.

Non-invasive CT fractional flow reserve

A new horizon in the field of coronary CTA is the introduction of non-invasive CT coronary fractional flow reserve (FFR-CT). It is hard to comprehend exactly how FFR-CT is derived, but it is predominantly based on fluid haemodynamics mathematical computation. The preliminary result of FFR-CT looks promising. In a study looking at 159 coronary vessels, FFR-CT had a good correlation with the referenced invasive FFR with a receiver-operator characteristics curve of 0.90. FFR-CT helped reduce the false positive findings of coronary CTA by 70% and improved the diagnostic accuracy of coronary CTA by 25%. It provides the much needed information about coronary flow, which is not currently obtainable on routine coronary CTA.

Conclusions

Coronary CTA has emerged as a very useful non-invasive imaging modality for the evaluation of CAD. Its main clinical role is in ruling out significant CAD in the low to intermediate pretest probability patients and in the setting of acute chest pain. Heavy calcification remains a major limitation of coronary CTA. With improved CT technology, the radiation dose of coronary CTA has decreased substantially. With the availability of functional information from cardiac CT stress perfusion and CT-FFR, coronary CTA poses to provide a one-stop investigation for anatomical and functional information of CAD.

Conflicts of interest

The authors have declared no potential conflicts of interest.

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