REVIEW

Multidetector computed tomographic angiography of the cardiovascular system

Joshua Burrill, Zaid Dabbagh, Frank Gollub, Mohamed Hamady

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The introduction of multidetector computed tomography (MDCT) is considered a dramatic development in CT imaging that has direct implication in the imaging of various systems, in particular the cardiovascular system. The advantages of MDCT are an enormous increase in imaging acquisition speed, more coverage of the patient, and high spatial resolution. This article reviews the recent developments in CT angiography and discusses the clinical application relevant to diagnosis and endovascular treatment of cardiovascular diseases.

See end of article for authors' affiliations

Correspondence to: Dr Joshua Burrill, Department of Interventional Radiology, St Mary's Hospital, Praed Street, London W2 1NY, UK; medicine@burrill.demon.co.uk

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The introduction of multidetector computed tomography (MDCT) is considered a dramatic development in CT imaging that has direct implications in the imaging of various systems, in particular the cardiovascular system. The advantages of MDCT are an enormous increase in imaging acquisition speed, more coverage of the patient, and high spatial resolution.

There are two main differences between conventional spiral CT and MDCT. Firstly, MDCT has a high acquisition speed (0.37 s rotation speed vs 1 s rotation speed for conventional CT); secondly, and probably more importantly, MDCT acquires volume data instead of individual slice data. These two factors together with thin section slices enable the new technique to provide almost isotropic data that can be arranged in different planes without compromising the spatial resolution of the original axial images.

This article reviews the recent developments in CT angiography (CTA) and discusses the clinical application relevant to diagnosis and endovascular treatment of cardiovascular diseases.

PRINCIPLES OF CT ANGIOGRAPHY

There are four main principles of CTA:

- Achieving good arterial contrast enhancement during image acquisition
- Providing adequate cephalocaudal coverage of the arterial system during optimum contrast opacification
- Imaging of the arterial tree during the first circulation of contrast to avoid venous artefact
- Efficient handling of the huge amount of acquired data using various post-processing algorithms including surface shaded display (SSD), volume rendering technique (VRT), multiplanar reconstruction (MPR) and maximum intensity projection (MIP).

IMAGING OF AORTO-ILIAC DISEASE

The indications for imaging of aorta and iliac system are summarised in box 1.

Using the new generation of CT scanners the thoraco-abdominal aorta can be covered within a single breath hold in between 11–22 s.[1] The amount of injected contrast ranges from 50–110 ml, depending on a patient's respiratory status, left ventricular function and the degree of anatomical details of the aorta branches needed clinically. Retrospective or prospective ECG synchronisation can be applied to obtain artefact-free images.[2] This is of particular clinical interest when aortic dissection is suspected.

Until recently open surgery was the only option to treat patients with aortic aneurysms. The endovascular stent graft has evolved in the last decade to provide an effective alternative to surgery in selected patients with aortic diseases (fig 1).[3] The key to successful aortic stent grafting is patient selection and appropriate planning. The factors that need to be taken into consideration in endovascular planning are: aneurysm neck of at least 1.5 cm below the renal arteries; absence of thrombus in the neck; neck angulations $<65°$; and favourable iliac anatomy. However, the arrival of fenestrated and branched stents allows treatment of short-necked and juxta-renal aneurysms. The stent graft should also be of appropriate length. Conventional angiography has long been the gold standard technique for evaluation of the aorto-iliac region. However, it is invasive and fails to assess accurately the mural thrombus, the exact diameter of the aortic aneurysm and the status of the aortic wall and surrounding structures.

CTA is a less invasive technique, more reliable in determining the aneurysm sac and more sensitive in detecting mural thrombus. CT scanning can also visualise the aortic wall to assess for inflammatory changes or detect rupture of the aortic aneurysm. The available software reconstructs hundreds of images and displays them in various three dimensional and two dimensional planes providing a very powerful tool for preoperative planning and postoperative follow up. The most important point

Abbreviations: ALARA, as low as reasonably achievable; CTA, computed tomographic angiography; DSA, digital subtraction angiography; DUS, Doppler ultrasound; EBCT, electron beam computed tomography; MDCT, multidetector computed tomography; MIP, maximum intensity projection; MPR, multiplanar reconstruction; MRA, magnetic resonance angiography; PE, pulmonary embolism; PVD, peripheral vascular disease; RAS, renal artery stenoses; SPECT, single photon emission computed tomography; SSD, surface shaded display; VDR, vessel density ratio; VQ, ventilation–perfusion; VRT, volume rendering technique

Box 1: Clinical applications of CT angiography

Thoraco-abdominal aorta

- Diagnosis of congenital and degenerative aortic diseases
- Assessment of acute aortic injuries and dissections
- Evaluation of visceral arteries (coeliac, superior mesenteric and renal arteries)
- Preoperative planning and follow up
- Tumour staging and surgical planning

Renal arteries

- Assessment of anatomy for donor transplants
- Diagnosis of renal artery stenosis in hypertensives or deteriorating renal function
- Assessment of renal arteries post-intervention (renal artery stenting)

Peripheral arterial system

- Assessment of peripheral vascular disease
- Assessment of bypass grafts

Carotid/intracranial circulation

- Characterisation of the atherosclerotic disease
- Assessment of aortic arch vessels
- Verification of internal carotid artery stenosis
- Preoperative planning of endovascular and surgical treatment of intracranial aneurysms and vascular malformations

Cardiac imaging

- Atypical chest pain
- Patients with intermediate risk
- Young patients with high risk for coronary disease
- Coronary artery anomalies
- Non-invasive follow-up following percutaneous transluminal angioplasty and stenting
- Assessment of myocardial scars, aneurysms, tumours and thrombi
- Assessment of coronary artery bypass grafts
- Assessment of the pulmonary veins before and following radiofrequency ablation

in the follow up of stent grafts is to exclude an endoleak into the aneurysm sac. It was found that CT angiography is more sensitive and specific than conventional angiography in detecting the presence of both endoleaks and faulty stents.[4] The superior image quality with the current MDCT angiography, especially those with 16 and 64 channel detectors, means that diagnostic angiography is rarely used for the planning or follow-up of endovascular aortic aneurysm repair at our centre.

IMAGING OF THE RENAL ARTERIES

The two main indications for renal angiography are to image the renal anatomy of live donors and to identify possible renal artery stenoses (RAS) in cases of suspected renovascular hypertension or in some cases of deteriorating renal function (box 1).

When imaging the renal anatomy of live donors the importance is in detecting any anatomical variations such as accessory arteries, early renal artery branching or venous anomalies, as these affect the difficulty and risk of complications in an operation which is being conducted for altruistic reasons.[5] It is also important to identify incidental renal pathology on the donor side such as renal cysts.

Studies looking at the sensitivity and specificity for the detection of accessory renal arteries using MDCT angiography have either used operative findings or digital subtraction angiography (DSA) as the gold standard. Studies report sensitivity between 80–100% with specificity between 96–100% in the detection of accessory renal arteries.[5–8] The sensitivity and specificity of the detection of early arterial branching was reported as 100% in one study,[6] although the sensitivity in another study was only 89%, with a specificity of 100%.[5] The different studies varied as to what they defined as venous anomalies with a sensitivity of between 97–100%[5–7]; however, one study had a relatively low sensitivity of 78% for minor venous variants.[7]

Renal artery disease is a curable cause of hypertension effecting 1–5% of patients with secondary hypertension.[9] Doppler ultrasound (DUS) is used to look for RAS although it has the disadvantages of requiring an expert user, relying on a reasonable patient body habitus, and being unreliable in detecting accessory renal arteries. DUS compared to DSA has a sensitivity of 75% and a specificity of 89.6% for RAS.[10] Both magnetic resonance angiography (MRA) and MDCT angiography are used to evaluate RAS. In one study there was no significant difference between the two, with sensitivities of 93% and 92%, respectively, and specificities of 100% and 99%, respectively, although in this study patient acceptance was higher for MDCT angiography.[11] MDCT angiography can also be used post-stenting to assess for recurrent RAS.

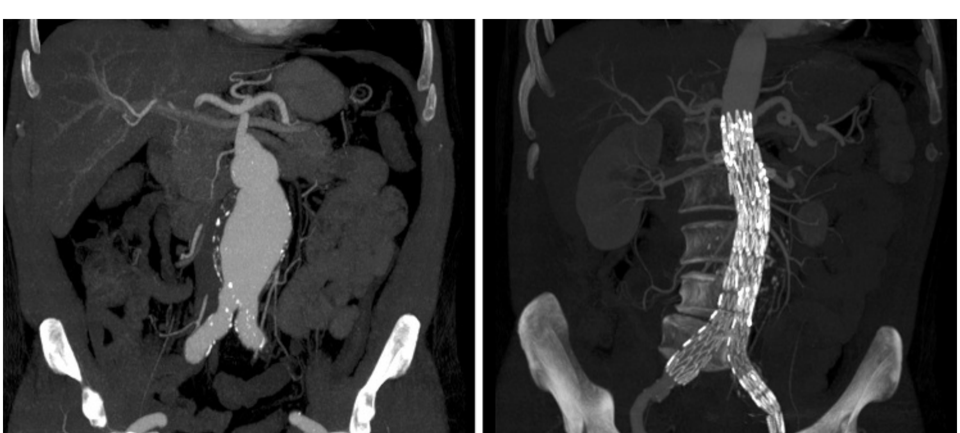

Figure 1 Abdominal aortic aneurysm. Multidetector computed tomography (MDCT) coronal reconstructions show a large abdominal aortic aneurysm pre- (left) and post-endovascular stenting (right).

For evaluating the renal anatomy of liver donors MDCT angiography has the advantage over MRA in that it is more acceptable to patients and misses fewer accessory renal arteries.[10] Although MDCT angiography involves radiation and a nephrotoxic contrast agent, kidney donors by their nature have good renal function where a single CTA has minimal negative effect when compared to the risk of complication due to not identifying an accessory renal artery. MDCT angiography ideally should not be used when a patient has poor renal function or an iodine allergy, although there is now concern about the use of some MRA contrast agents and the risk of nephrogenic systemic fibrosis.

IMAGING OF PERIPHERAL VASCULAR DISEASE

The indications for imaging of the peripheral arterial tree are summarised in box 1. DUS and pressure measurement studies are widely used to assess peripheral vascular disease (PVD). However, the presence of diffuse disease and heavy vascular calcification makes using these studies alone suboptimal in many cases. DUS is also operator dependent and can therefore not provide reliable evidence of extraluminal abnormalities such as cystic adventitial disease, popliteal entrapment and the bony status in trauma cases.

Although digital subtraction angiography remains the gold standard technique for evaluating PVD, CTA provides a relatively quick and non-invasive technique, which covers a wide region of the body with high spatial resolution. The additional advantages of CTA are the visualisation of the extraluminal pathology, including aneurysms, as well as comprehensive review of visceral injuries and fractures in trauma patients. MDCT angiography provides better assessment of eccentric lesions and visualisation of more arterial segments, particularly in occlusive arterial disease. The sensitivity and specificity of MDCT angiography in comparison to DSA are reported to be between 93–100%.[12–15] In a recent systematic review of 10 studies, including 400 patients, comparing angiography and MDCT angiography, the pooled sensitivity and specificity were, respectively, 92% (95% confidence interval (CI) 87% to 95%) and 91% (95% CI 87% to 95%) for the aorto-iliac level, 96% (95% CI 94% to 99%) and 85% (95% CI 73% to 89%) for the femoro-popliteal level, and 91% (95% CI 85% to 97%) and 85% (95% CI 72% to 97%) for infra-popliteal level. However, there has been significant heterogeneity among the studies in terms of scan generation and scan protocol, and probably patient selection bias. This meta-analysis concluded that MDCT angiography has high diagnostic value when compared with the reference standard test. The challenges for CTA in this part of the body include: injection of a large amount of contrast (120–160 ml); speed coverage, which should not exceed 50 mm/s to avoid the image acquisition running ahead of contrast column; and the need for imaging post-processing since the number of the acquired slices is so large that they cannot be handled by viewing the axial images alone. Several protocols have been suggested to optimise vessel enhancement and reduce the total amount of injected contrast.[16–18]

The available post-processing algorithms still have their own limitations. The MIP (maximum intensity projection) and VDR (vessel density ratio) exaggerate the degree of stenosis when there is calcified plaque. The MPR (multiplanar reconstruction) cannot follow the tortuous or off plane course of some arteries, as is usually the case with the lower limb arteries. Several solutions are being investigated to overcome these technical problems including curved MPR and digital subtraction. Also, the current state of the art generation of 64 MDCT has not been thoroughly investigated.

IMAGING OF PULMONARY ARTERIES

Although selective pulmonary angiography is considered the standard reference test,[19] there is strong doubt about the clinical usefulness and reproducibility of this examination. Pulmonary angiography is an invasive modality[20 21] with significant inter-observer disagreement rates ranging between 34–55%.[22 23]

Some centres still consider a ventilation–perfusion (VQ) scan the first line modality in diagnosis of pulmonary embolism (PE). However, this test suffers from a high percentage of intermediate results (73%)[24] and poor inter-observer agreement.[25] Nevertheless, its role might improve if revised criteria of interpretation of VQ scan[26 27] and newer technology such as single photon emission CT (SPECT) are introduced in practice.[28] MRA has shown suboptimal resolution in detection of small PEs.[29 30] Moreover, MRA is not widely available and a relatively long examination time is involved.

MDCT has the ability to cover the pulmonary artery tree with sub-millimetre slices in a 10 s breath hold. This feature makes CT pulmonary angiography a first-line diagnostic imaging modality in the management of PE in many centres (fig 2).

The main advantage of this technique is the ability to evaluate the pulmonary vessels together with lung parenchyma and mediastinum. Studies have shown that more than two thirds of patients with a provisional diagnosis of PE may receive either an alternative or additional diagnosis such as aortic dissection or pneumothorax.[31 32]

In addition CT has demonstrated better inter-observer agreement than nuclear medicine.[33] Moreover, CT is more cost effective than other investigations that do not include CT, such as pulmonary angiography and VQ studies.[34]

MDCT with 16-row detectors can cover the whole thorax with millimetre or sub-millimetre resolution within a short breath-hold of less than 10 s, which is crucial for sick patients. This high spatial resolution of 1 mm makes evaluation of the pulmonary tree down to the sixth order pulmonary artery branches possible with a lower percentage of non-diagnostic studies.[35 36] Also the near isotropic data with in-plane and through-plane resolution make two and three dimensional visualisation a reality and enables the images to be displayed in all planes without compromising spatial resolution.

Although the development of MDCT has led to improved detection of small peripheral pulmonary emboli, the clinical significance of such findings is uncertain. It is unclear whether treating patients with very small pulmonary emboli will improve final outcome.[37–39] Nevertheless, investigators have suggested that withholding anticoagulation in patients with negative CT pulmonary angiography is a safe practice.[40]

CAROTID ARTERIES

Atherosclerotic disease of the carotid arteries is responsible for a significant number of ischaemic strokes. Carotid intervention in both symptomatic and in some asymptomatic patients has proven beneficial in preventing further strokes (fig 3).[41 42]

Accurate estimation of the degree of stenosis is crucial for optimising the benefits from carotid surgery or stenting. DSA is the current gold standard; however, it carries a small but significant risk of complications (1.3%).[43]

Beside other non-invasive imaging modalities such as DUS and MRA, MDCT angiography can provide an important diagnostic tool. The intracranial as well as extracranial neurovascular axis can be evaluated in the same sitting. In a recent study of 37 patients and 73 vessels, the reported sensitivity and specificity for high grade stenosis were 75% and 96%, respectively, and for moderate stenosis 88% and 82%, respectively.[44] Furthermore, MDCT can assess the composition of the atherosclerotic plaque and the haemodynamics of the

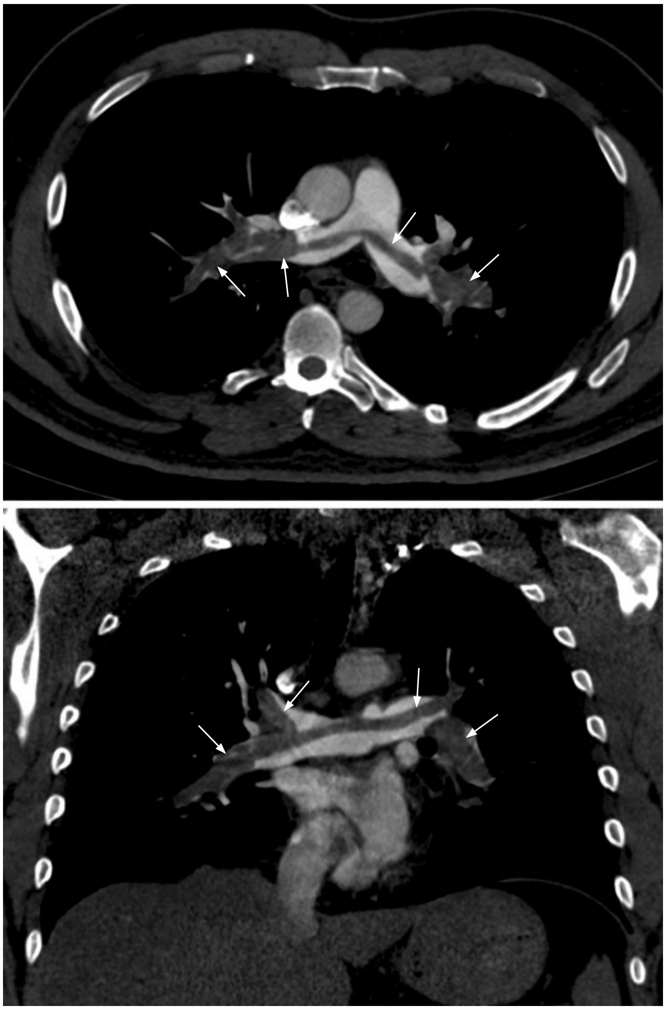

Figure 2 Pulmonary embolism. Contrast enhanced axial (top) and coronal (bottom) CT images showing a large saddle embolus within the main pulmonary trunk and the pulmonary arteries bilaterally (arrows).

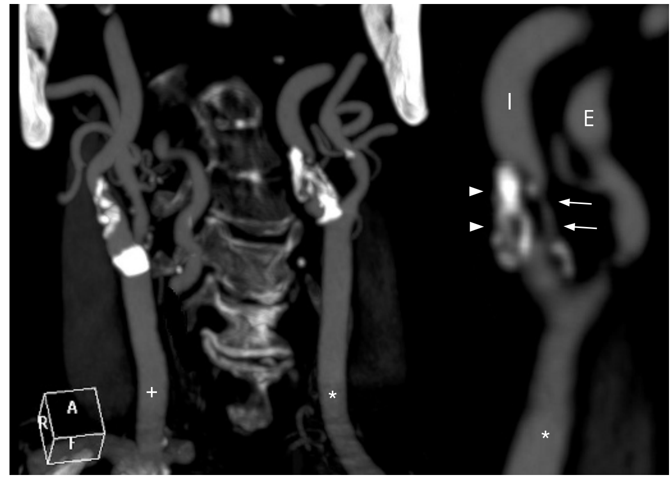

Figure 3 Coronal MDCT angiography of the carotid arteries showing a 90% stenosis (arrows) of the left internal carotid artery (I) with calcification of the origin (arrowheads). The right (+) and left (*) common carotid arteries, left internal (I) and external (E) carotid arteries can also be seen.

brain circulation by using the CT brain perfusion.[45 46] Nevertheless, the exact role of MDCT in the management of carotid disease needs to be further defined.

CARDIAC IMAGING

Ischaemic heart disease is the most common cause of premature death in western society. The need for an early screening tool is necessary to reduce the high mortality associated with acute cardiac events. MDCT can be a helpful screening modality to detect and quantify coronary calcium scoring, detect haemodynamically significant stenoses, and study the atherosclerotic plaque non-invasively (fig 4).

MDCT with a very short rotation time of 0.37 ms allows acquisition of up to 64 contiguous slices combined with prospective or retrospective ECG triggering to obtain artefact-free images. The examination is completed in a single breath hold. Due to the ultrafast scanning time, MDCT is able to obtain several sets of data in one cardiac cycle. With retrospective ECG gating the heart volume is covered continuously with 1 mm collimation providing temporal resolution of 83 ms and isotropic spatial resolution of 0.4 mm.

The sensitivity and specificity of calcium scoring in predicting a cardiac event underwent thorough investigation in several large trials.[47–49] Calcium scoring can be used as an additional tool for risk stratification and it is particularly suited for patients with intermediate risk. The current indications for cardiac imaging are summarised in box 1.

CT coronary angiography is competing with the established but invasive technique of percutaneous coronary angiography. Ropers *et al* studied 84 patients with suspected coronary disease using 64 MDCT. The reported sensitivity and specificity were 95% and 93%, respectively, with negative predictive value of 98%.[43] In another study involving 103 patients using 16 MDCT, the sensitivity and specificity were 95% and 97%, respectively, with negative predicative value of 94%.[44] However, several challenges are still facing the visualisation of coronary arteries in CT scanning, including a heart rate more than 60 beats/min, cardiac arrhythmias, severe vessel calcification, vessel diameter <1.6 mm, and visualisation of all coronary artery segments. Maruyama *et al* showed that MDCT had sensitivity and specificity for visualised segment stenosis of 90% and 99%, respectively. However, MDCT could only visualise 74% of diseased segments, with conventional coronary angiography being the reference standard.[50]

As compared to conventional coronary angiography the current generation of 16 and 64 slice MDCT scanners and the available reformatting techniques still have lower sensitivity and specificity for detecting atherosclerosis. Nevertheless, the introduction of the newest technology in this field, such as 256 slice MDCT and dual source CT, makes this imaging modality a very promising screening as well as diagnostic tool for cardiac patients. Clinically the role of MDCT is likely to be limited in patients with a high pre-test probability of having significant disease, since those patients will inevitably need percutaneous intervention. However, non-invasive CT coronary angiography would be preferable for patients with intermediate or low risk of significant disease.

RADIATION DOSE

As the use of MDCT becomes widespread, the importance of radiation dose has been highlighted. Initial studies in cardiac CT by Hunold *et al* demonstrated that both calcium scoring and coronary artery CT angiography involve a lower average effective dose with electron beam CT (EBCT) than with MDCT.[51] Catheter coronary angiography has a higher effective dose, on average, than EBCT angiography, although lower than that of MDCT. Although effective dose increases, both scan time and the amount of nephrotoxic iodinated contrast needed for an MDCT angiogram is reduced when compared to EBCT.[52]

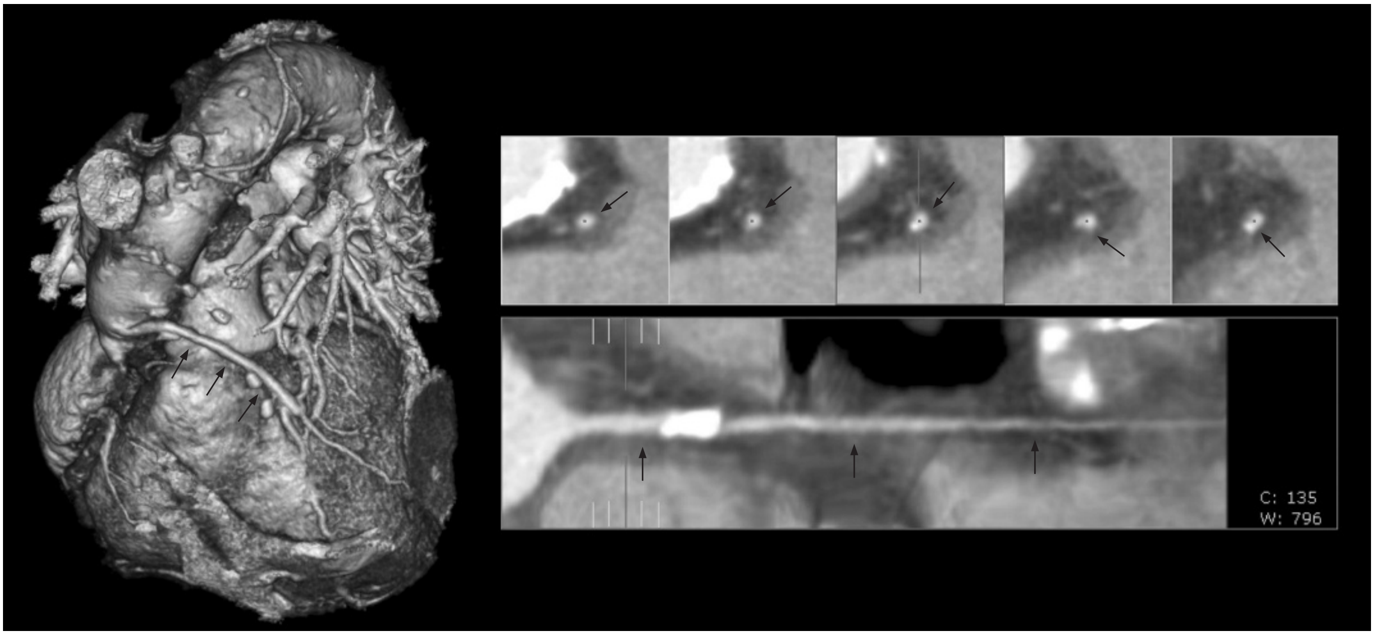

Figure 4 CT coronary angiography. Reconstructed CT images using proprietary software which automatically provides a three dimensional cardiac image and allows selection of specific cardiac vessels and in this case a vein graft (arrows). This generates an opened-out reconstruction to identify stenoses. Some vessel calcification is seen but no stenosis.

A number of methods have been used to reduce radiation dose when doing cardiac scans with MDCT. The technique of ECG pulsing involves modulating the mAs of the scanner depending on the cardiac cycle, and this has been shown in a review article to approximately halve the effective dose of an MDCT coronary angiogram.[53]

Unlike coronary angiography, peripheral angiography shows a general decreased dose when carried out using MDCT as opposed to conventional DSA techniques. An early study by Rubin *et al*[18] demonstrated that the radiation exposure for DSA of the lower extremity arteries was approximately 3.9 times greater than for MDCT angiography, a fact, if not a figure, confirmed elsewhere.[54 55] Further studies comparing EBCT with MDCT, and four and eight channel MDCT angiography, confirms that eight channel scanners are quicker and involve less contrast than either EBCT or four channel scanners, with a similar radiation dose.[52 56]

General dose reducing techniques have been shown to provide successful dose reduction without compromising diagnostic success when conducting MDCT angiography. Decreasing mAs has been shown not to affect the diagnostic sensitivity of MDCT angiography, with a substantial reduction in radiation dose.[57 58] Wintersperger *et al*[59] demonstrated that a reduction in kVp, from 120 to 100, significantly reduced patient dose. A reduced kVp reduces the signal-to-noise ratio. This reduction is compensated for by the attenuation level of iodine, leading to diagnostic images. While these techniques help to keep dose "As Low As Reasonably Achievable" (ALARA), some advances have to be made before MDCT coronary angiography is on a par with DSA.

CONCLUSION

The revolution in CT technology, including high scanning speed, wider coverage area and high temporal and spatial resolution, is providing a credible, non-invasive diagnostic tool for a wide range of cardiovascular diseases and will likely replace catheter diagnostic angiography in most vascular beds in the near future. However, cost effectiveness studies and strong evidence data on its clinical utility are still lacking.

Main points

- MDCT angiography is used to assess the cardiovascular system either before or after treatment and is useful in planning and confirming the need for endovascular procedures.
- DSA is still considered the gold standard; however, non-invasive angiographic techniques are approaching, and in some cases reaching, 100% sensitivity and specificity.
- The contraindications for MDCT angiography are identical to conventional CT, and although the radiation dose is higher for MDCT angiography than for EBCT, it is lower than it is for DSA and requires a smaller amount of iodinated contrast.

Points for the non-specialist

- Multidetector CT scanners have an increase in acquisition speed and high spatial resolution resulting in high quality angiographic imaging.
- Evaluation of the cardiovascular system is therefore possible without using invasive conventional angiographic techniques.
- In some cases, such as pulmonary angiography, MDCT has completely replaced conventional angiographic techniques.
- MDCT angiography is particularly useful in clinical situations where there is a low incidence in the at-risk population, such as renal artery stenosis, and therefore only a small proportion with the diagnosis need to go on to have an invasive endovascular procedure.

Authors' affiliations
Joshua Burrill, Frank Gollub, Mohamed Hamady, Department of Interventional Radiology, St Mary's Hospital, London, UK
Zaid Dabbagh, Department of Radiology, Chase Farm Hospital, Enfield, Middlesex, UK

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