Current status of non-invasive coronary angiography for the diagnosis of coronary artery stenosis

KAENG W LEE, JONATHAN PANTING

Abstract

Recently, several techniques for non-invasive imaging of the coronary artery have emerged as promising alternatives to conventional coronary angiography for the diagnosis of coronary artery stenosis. Such imaging modalities include magnetic resonance imaging, electron-beam computed tomography and multi-slice computed tomography. With these technologies, images can be acquired rapidly with high temporal and spatial resolution. In their current state of development, non-invasive techniques can reliably be used to visualise significant stenosis of the proximal and mid portions of the coronary tree. However, complete assessment can be hindered by calcification in the vessel wall and by motion artefact.

Key words: computed tomography, coronary angiography, coronary artery disease, magnetic resonance imaging.

Br J Cardiol (Acute Interv Cardiol) 2006;**13**:AIC 49–AIC 56

COPYRIGHT MEDINEWS (CARDIOLOGY) LIMITED REPRODUCTION PROHIBITED

Introduction

Invasive coronary angiography (ICA) is generally accepted as the reference 'gold standard' for visualisation of coronary arteries and the assessment of coronary artery stenosis. The technique provides excellent temporal and spatial resolution and also allows percutaneous intervention to be performed at the same session. However, ICA is limited by its invasiveness. It is associated with a small but finite risk of serious complications, including stroke or death. Moreover, at least 20% of the diagnostic ICA procedures performed each year reveal no evidence of obstructive coronary artery disease (CAD). Thus, there is a growing interest in non-invasive technologies to diagnose and visualise obstructive coronary artery disease.

Non-invasive imaging of the coronary arteries is difficult due to their complex anatomy, small size, tortuous course, and movement during cardiac contraction and respiratory motion. The ideal modality needs to have a high temporal and spatial resolution with three-dimensional (3-D) capabilities for visualisation of the whole coronary arterial tree within a short total examination duration, and acquisition must be synchronised to the cardiac cycle (with ECG gating). Over recent years, these non-invasive modalities have evolved rapidly, leading to improvements in image quality and an increase in diagnostic accuracy for coronary artery stenosis. This article will provide a brief overview of technical developments, recent clinical studies and the possible clinical applications of the three most promising non-invasive imaging modalities for the detection of coronary artery stenosis (table 1). These are coronary magnetic resonance angiography (CMRA), multi-slice spiral/helical computed tomography (MSCT) and electron beam computed tomography (EBCT). (Detailed discussion in the characterisation of coronary plaque vulnerability by these non-invasive imaging methods is beyond the scope of this article.)

Table 1. Acquisition parameters of invasive coronary angiography and the newer generation of non-invasive coronary imaging modalities

	ICA	Spiral CMRA	64-slice MSCT	EBCT
Temporal resolution	5–20 ms	20 ms	80–90 ms	33–100 ms
Spatial resolution	0.2 mm	0.7 mm	0.4 mm	0.6 mm
Isotropic pixels	–	No	Yes	No
Cardiac cycles/image	–	20–30	1	1

Key: ICA = invasive coronary angiography; CMRA = coronary magnetic resonance angiography; MSCT = multi-slice spiral/helical computed tomography; EBCT = electron beam computed tomography

Magnetic resonance coronary angiography

Magnetic resonance imaging (MRI) has transformed our clinical practice in the last 20 years but only recently has it become possible to capture a beating heart. Using sophisticated computer technology, high-strength magnets, rapid acquisition software and contrast agents, it is now possible to obtain images of the heart that are unlike any other imaging modality. However, CMRA remains a major challenge because of both the fast

Cardiology Department, Heart of England NHS Trust, Solihull Hospital, Solihull, West Midlands, B91 2JL.
Kaeng W Lee, Specialist Registrar in Cardiology
Jonathan Panting, Consultant Cardiologist
Correspondence to: Dr J Panting
(email: Jonathan.Panting@heartofengland.nhs.uk)

Table 2. Sensitivity and specificity of magnetic resonance coronary angiography studies for the detection of coronary artery stenosis in comparison to invasive coronary angiography

	Year	Patients (n)	Sensitivity (%)	Specificity (%)	Temporal resolution (ms)	*Study excluded (%)
First generation 2-D breath-hold						
Manning *et al.*[1]	1993	39	90	92	80–104	6
Post *et al.*[2]	1997	35	63	89	88–113	11
Pennell *et al.*[39]	1996	39	85	–	126	–
Second generation 3-D respiratory gating, retrospective algorithm						
Kessler *et al.*[40]	1997	73	65	88	125	48
Muller *et al.*[41]	1997	35	83	94	125	14
Van Geuns *et al.*[42]	1999	32	50	91	128	26
Sandstede *et al.*[43]	1999	30	81	89	230	23
Sardanelli *et al.*[44]	2000	42	82	89	–	14
Nikolaou *et al.*[45]	2001	40	72	60	–	27
Third generation 3-D respiratory gating, prospective algorithm						
Kim *et al.*[3]	2001	109	93	42	–	16
Sommer *et al.*[4]	2002	107	88	91	–	28
Plein *et al.*[5]	2002	40	74	88	–	13
Third generation, 3-D breath-hold						
Van Geuns *et al.*[7]	2000	38	68	97	110	31
Regenfus *et al.*[9]	2000	50	87	91	126	23
Yang *et al.*[8]	2003	40	76	91	34	22
Regenfus *et al.*[6]	2003	61	85	90	–	23

*Note that in most studies unevaluable segments were excluded from analysis

COPYRIGHT MEDINEWS (CARDIOLOGY) LIMITED REPRODUCTION PROHIBITED

motion of the coronary arteries during cardiac contraction and motion due to respiration. CMRA therefore requires very high temporal resolution techniques.

Developments of CMRA

Early CMRA used two-dimensional (2-D) techniques that were based on the acquisition of multiple parallel or oblique sections. These required multiple breath-holds to obtain sufficient images to cover all parts of the coronary artery tree.[1,2] The misregistration of contiguous sections due to inconsistent breath-hold positions frequently created interpretation difficulties. Other problems were motion artefact, long scanning time, inadequate resolution and poor reproducibility.

More recently, motion artefact has been reduced using navigator echos to monitor diaphragmatic motion in real time.[3-5] Using this technique, respiratory gating can be performed either prospectively or retrospectively after image acquisition. One other technique developed recently is the 3-D breath-hold technique.[6-8] With this technique, an entire 3-D volumetric coronary data acquisition (consisting of contiguous sections) can be obtained during a short (about 15 seconds) breath-hold interval, thus eliminating problems with diaphragm movement. The combination with real-time slice positioning and other higher-resolution acquisition schemes, such as spiral imaging and contrast enhancement, can further facilitate the use of these techniques and improve the diagnostic sensitivity.[8,9]

Currently used protocols achieve temporal resolution of approximately 125 ms and spatial resolution of 1.2 x 1.2 x 1.4 mm^3.[10] However, the recent introduction of 3T high-field MR scanners may permit submillimeter resolution. In addition, intravenous contrast agents may be used to increase the signal-to-noise ratio (SNR) of the coronary artery.

Clinical studies

The clinical studies of CMRA are summarised in table 2. A variety of imaging techniques have been employed for these studies. Of note, these clinical studies were usually performed in relatively small patient groups, and overall, wide ranges of sensitivity and specificity were reported – sensitivity 38% to 83%, specificity 57% to 95%. These results indicated only moderate accuracies, even when the images of poor quality were excluded.[11]

A recent meta-analysis[11] of all clinical studies on the diagnostic performance of CMRA published between 1991 and January 2004 has shown that in subjects with intermediate/high likelihood for CAD, CMRA can detect about three-quarters of significant stenoses in the visualised segments of the major epicardial coronary arteries, with a concomitant specificity of 86%. Of

Panting pp AIC49-AIC56:Panting pp AIC49-AIC56 4/8/06 4:56 pm Page 3

note, the published reports included in the meta-analysis were quite heterogeneous regarding study design and analytic methodologies and thus their findings should be used cautiously when attempting to support the clinical utility of CMRA.

With the latest MR technologies, Jahnke *et al.*[10] studied 55 consecutive patients with suspected CAD who underwent free-breathing, navigator-gated CMRA using a single 3-D volume with transverse slice orientation and high spatial resolution that allowed coverage of the entire coronary arterial tree during a single MR measurement. Almost all main epicardial vessels, including their distal segments and major side branches, were reliably visualised and, of these, 83% were evaluable with an overall diagnostic sensitivity, specificity and accuracy of 78, 91 and 89%, respectively.

Limitations

In most clinical studies included in the meta-analysis, patients with surgical clips and other metallic implants (such as pacemakers, implantable defibrillators or coronary stents) were excluded from participation as these structures impair image quality of the coronary arteries or are unsafe in the strong magnetic field. Besides metallic structures, other high-density structures such as calcified plaques also hamper the acquisition with CMRA. Claustrophobic patients are unsuitable for CMRA. In addition, the vast majority of the CMRA studies did not evaluate distal segments of the coronary vessels due to poor visualisation of the distal coronaries and branch vessels.[11]

However, CMRA has several advantages over other modalities as it provides excellent soft tissue contrast, has inherent 3-D capabilities and allows acquisition in any anatomical plane. CMRA does not expose the patient to radiation, nor iodinated contrast, making this the safest of the current non-invasive modalities. Besides direct visualisation of coronary arteries, quantification of velocity and flow are also possible. Moreover, cardiac MRI is established as a reliable and clinically important technique for assessment of cardiac structure, function, perfusion and myocardial viability. Such versatility and accuracy is unmatched by any other individual imaging modality.[12,13]

Perspective

CMRA techniques are constantly improving through hardware and acquisition sequence development. New intravascular contrast agents may also increase image quality through improved signal-to-noise and contrast-to-noise ratios. In time, these tools will combine to provide a robust and uncomplicated coronary angiographic technique, delivering information on coronary artery anatomy (obstruction and plaque vulnerability), as well as myocardial blood flow and microvascular integrity in a single examination. Both cardiologists and radiologists are optimistic about these future possibilities.[13,14]

CT technologies for non-invasive coronary angiography

Currently, two competing CT technologies are available for non-invasive coronary imaging. One (EBCT) uses a scanning beam of electrons that are steered by an electromagnetic deflection system onto a series of fixed 'target' rings arranged in a semicircular manner around the patient. The other (MSCT) involves the mechanical motion of the table and X-ray tube around the patient, combined with multiple detectors to acquire the data in a spiral or helical fashion. Both techniques can be used for quantification of coronary plaque calcium (an indicator of coronary risk) as well as for non-invasive coronary angiography. Diagnoses concerning the presence of coronary artery stenosis are usually made based on the axial cross-sectional images. Two-D or 3-D reconstruction techniques may be helpful in presenting the data but add little incremental diagnostic value.[15] It is important to emphasise that MSCT and EBCT only provide anatomical images, visualising the presence of atherosclerosis; information on the haemodynamic significance of these lesions (i.e. ischaemia) cannot be derived. Another limitation of all non-invasive angiography is the relative inability to visualise collaterals.

Table 3. Comparisons of acquisition parameters of MSCT: 4- *vs.* 16- *vs.* 64-slice systems

	4-slice MSCT	16-slice MSCT	64-slice MSCT
Temporal resolution	125–250 ms	90–200 ms	80–90 ms
Spatial resolution	0.5 x 0.5 x 1.3 mm	0.5 x 0.5 x 0.6 mm	0.0 x 0.3 x 0.4 mm
Gantry rotation	500 ms	420 ms	330 ms
Scanning time	30–40 s	10–15 s	< 12 s
Contrast dose	150 ml	50 ml	50 ml

COPYRIGHT MEDINEWS (CARDIOLOGY) LIMITED REPRODUCTION PROHIBITED

Multi-slice computed tomography

Over the past few years, we have seen a spectacular development of image quality obtained by using contrast-enhanced MSCT for visualisation of the coronary arteries and detection of CAD with increasing accuracy.[16] These scanners have the potential to allow non-invasive coronary angiography by use of a rotation speed of less than 500 ms and sophisticated algorithms for either retrospective or prospective ECG gating. After injection of non-ionic, iodine-based contrast medium, the entire heart can be scanned within a single breath hold. The reconstruction of images can be conducted using data acquisition at any arbitrary time point within the heart cycle (usually mid-to-late diastolic phase) by use of dedicated image software algorithms. Various post-processing techniques can be used to display the coronary arteries.[17]

Development from 4-slice to 64-slice MSCT

The initial 4-slice MSCT scanners have been available for general purpose scanning since 1999.[18] With this technique, simultaneous acquisition of four slices, half-second scanner rotation and

Table 4. Sensitivity and specificity of multi-slice computer tomography studies for the detection of coronary artery stenosis in comparison to invasive coronary angiography

	Year	Patients (n)	Mode of analysis	Sensitivity (%)	Specificity (%)	Unevaluable segments (%)
4-slice CT						
(segments > 2.0 mm)						
Achenbach *et al.*[19]	2001	64	Per-artery	85	76	32
Knez *et al.*[20]	2001	44	Per-artery	84	97	6
Nieman *et al.*[21]	2001	31	Per-segment	81	97	27
Martuscelli *et al.*[26]	2004	64	Per-artery	89	98	16
16-slice CT						
Nieman *et al.*[22]	2002	59	Per-artery	95	86	7
Ropers *et al.*[46]	2003	77	Per-artery	92	93	12
Mollet *et al.*[47]	2004	128	Per-segment	92	95	–
Mollet *et al.*[48]	2005	51	Per-segment	95	98	–
Hoffman *et al.*[29]	2004	33	Per-segment	63	96	–
Hoffman *et al.*[49]	2005	103	Per-segment	95	98	6.4
Kuettner *et al.*[27]	2005	72	Per-segment	82	98	7
Kuettner *et al.*[28]	2005	124	Per-segment	85	98	15
64-slice CT						
(all segments)						
Achenbach *et al.*[23]	2005	50	Per-segment	92	95	5
Leschka *et al.*[24]	2005	67	Per-segment	94	97	–
Raff *et al.*[25]	2005	70	Per-segment	86	95	12
Mollet *et al.*[31]	2005	52	Per-segment	99	95	–

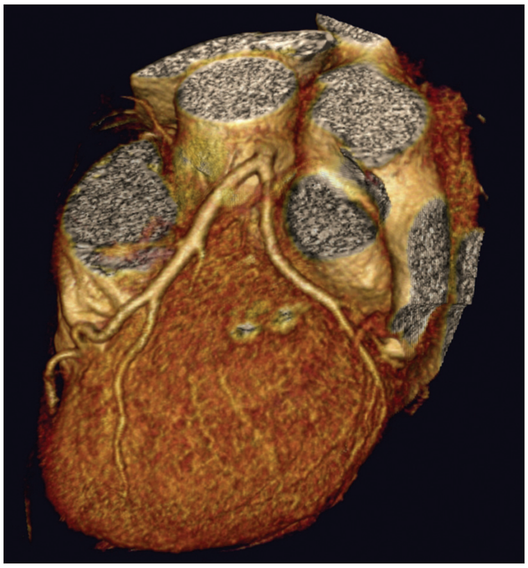
COPYRIGHT MEDINEWS (CARDIOLOGY) LIMITED REPRODUCTION PROHIBITED

up to 125 ms maximum temporal resolution can be achieved with a slice thickness of 0.75–1.3 mm (table 3). Early clinical studies have shown reasonably good diagnostic capability for obstructive CAD with this first generation of MSCT.[19-21] However, up to 32% of all coronary segments had to be excluded from analysis because of image degradation by motion artefact especially of the right coronary artery and the circumflex artery.[19]

With the availability of 16-slice scanners,[22] the sensitivity and specificity for detection of significant coronary artery stenosis exceed 90%. The 16–detector row systems enable faster scanning (420 ms per rotation with 100 ms temporal resolution) and thinner image sections (0.6 mm) and have shown significant improvements in coronary imaging in several clinical studies. Although the 16-slice MSCT scanners provide promising results, some segments (about 20%) cannot be evaluated, in most cases due to severe vessel wall calcification or insufficient suppression of cardiac motion artefact. Moreover, in some studies the evaluation was limited to branches having a diameter of > 2 mm.

With the advent of the latest generation of 64-MSCT systems,[23-25] equipped with more and thinner detector rows and increased rotation scan speed, previous limitations may be mitigated as a result of even faster image acquisition, better spatial and temporal resolution, and more rapid post-processing compared with prior generations. These scanners can provide 0.4

Figure 1. An example of a 3D reconstruction of a 64 multi-slice CT data set. This shows the left coronary artery with a good view of both the circumflex and LAD with visualisation of proximal side branches



Panting pp AIC49-AIC56:Panting pp AIC49-AIC56 4/8/06 4:56 pm Page 5

Table 5. Sensitivity and specificity of electron-beam computed tomography studies for the detection of coronary artery stenosis in comparison to invasive coronary angiography

	Year	Patients (n)	Sensitivity (%)	Specificity (%)	Unevaluable segments (%)
Nakanishi *et al.*[50]	1997	37	74	94	12
Schmermund *et al.*[51]	1998	28	82	88	28
Reddy *et al.*[52]	1998	23	88	79	10
Achenbach *et al.*[33]	1998	125	92	94	25
Budoff *et al.*[53]	1999	52	78	91	11
Rensing *et al.*[54]	1998	37	77	94	19
Achenbach *et al.*[55]	2000	36	92	91	20
Leber *et al.*[56]	2001	87	78	93	24
Ropers *et al.*[57]	2002	90	90	66	24
Nikolaou *et al.*[58]	2002	20	85	77	11

mm nearly isotropic voxels in a rotation time of 330 ms. The 0.4-mm spatial resolution can visualise a septal artery smaller than 1.5 mm in diameter and define plaque in the coronary arteries.

Moreover, the scanning time is shortened to < 12 s, allowing a decreased breath-hold time, better exploitation of contrast media with less enhancement of adjacent structures, and a lower dose of applied contrast media. The improved resolution also translates into better multiplanar and 3-D reconstructions. With the dissemination and further development of the 64-slice MSCT, investigators will become more and more ambitious in including even smaller (< 1.5 mm) distal arterial segments and side branches. An example of a 3-D reconstruction of a left coronary artery is shown in figure 1.

The increased scan speed and thinner collimated slice widths achieved with this latest generation machine are indispensable for high-resolution angiography of the coronary arteries and reliable coronary stenosis detection. To become a clinically accepted tool for the examination of patients with suspected CAD, the main requisite for CT coronary angiography will be the complete visualisation of all therapeutically relevant coronary arteries without excluding segments. Indeed, there is a clear tendency towards a reduced proportion of coronary segments whose image quality precludes evaluation. The first clinical experiences with the 64-slice CT scanner reported by Leschka *et al.*[24] indicated that all coronary arteries with a diameter of > 1.5 mm can be evaluated, without exclusion. In addition, none of the coronary segments of the 67 consecutive patients with suspected CAD needed to be excluded from analysis, and all 20 patients without significant stenosis on invasive angiography were correctly identified.

Clinical studies

The clinical studies using MSCT are shown in table 4. Using 4- to 8-slice CT, sensitivity ranges between 72–93% and specificity ranges between 84–98% for detection of coronary stenosis have been reported.[19-21,26] Using 16-slice CT, overall sensitivity, including all segments, was reported to range from 73% to 95% and specificity from 86% to 96%, for detection of obstructive disease, depending on the diameter of the segments, the mode of analysis and the patient selection criteria.[27-29] A more recent study evaluated 94% of a total of 298 native coronary artery segments studied with 16-slice MSCT and demonstrated a sensitivity of 93% and a specificity of 91% without excluding the 6% of segments that were uninterpretable.[30]

With the 64-slice CT scanner, Leschka *et al.*[24] reported an overall sensitivity for classifying stenosis of 94%, specificity 97%, positive predictive value (PPV) 87%, and NPV (negative predictive value) 99%. These results represent a significant improvement over the previous platforms of MSCT and similar results have been demonstrated by another recent study.[25] On a segment-by-segment analysis, Mollet *et al.*[31] also reported similar sensitivity, specificity, PPV and NPV of 64-slice MSCT for detecting significant stenosis of 99%, 95%, 76% and 99%, respectively. All available coronary segments, regardless of size, were included in the evaluation. Mean scan time was 13.3 ± 0.9 seconds.

MRA versus MSCT: head-to-head comparison

A recently published head-to-head comparison of 3-D CMRA and 16-slice MSCT in the detection of coronary artery stenosis indicated that both imaging modalities have similar sensitivity (75% *vs.* 82%) and specificity (77% *vs.* 79%, respectively) when it comes to detecting coronary diameter stenosis by visual assessment.[32] Neither modality was as accurate as quantitative coronary angiography (QCA), although the use of quantitative analysis significantly improved the diagnostic accuracy of MSCT but not that of CMRA. Given its shorter acquisition time, lower cost and better image quality, MSCT might be preferred over CMRA in clinical practice for the detection of coronary stenosis. However, MSCT is disadvantaged by the requirement for contrast injection and radiation exposure.

Electron-beam computed tomography

Since its first clinical appearance in 1984, EBCT has made signif-

COPYRIGHT MEDINEWS (CARDIOLOGY) LIMITED REPRODUCTION PROHIBITED

Panting pp AIC49-AIC56:Panting pp AIC49-AIC56 4/8/06 4:56 pm Page 6

icant development. The typical temporal resolution for most standard EBCT can now achieve 50 or 100 ms per slice, with the latest generation units capable of achieving an astonishing temporal resolution as low as 33 ms. EBCT is a cross-sectional CT technique with the two detector arrays simultaneously acquiring two contiguous images of 1.5 mm with prospective triggering to the ECG. Intravenous injection of iodinated contrast medium permits visualisation of the coronary arteries within one breath-hold.[15]

To date, the clinical application of EBCT in the investigation of CAD has primarily been a screening tool for coronary calcifications. The application of EBCT could be extended from screening for coronary calcium, a measurement of plaque burden, to the actual visualisation of coronary stenosis using contrast-enhanced EBCT angiography. However, low spatial resolution and high image noise limit the image quality and prevent adequate visualisation of many coronary segments. Because of this, only the proximal and middle segments of the major coronary arteries have been evaluated for the presence or absence of stenosis and occlusions in most clinical studies.[15]

Clinical studies

Clinical studies using EBCT are summarised in table 5. In general, the sensitivity of EBCT ranged from 74% to 92%, with specificities from 66% to 94%, for the detection of significant stenotic coronary lesions and occlusions in the proximal and middle segments of coronary vessels. The largest series of EBCT angiography reported sensitivities of 92% and specificities of 94%, with an overall accuracy of 93% for identifying significant coronary stenosis in those coronary arteries evaluable.[33] In a recent head-to-head comparison between EBCT (n=101) and MSCT (n=91) for the detection of significant coronary stenosis (> 50%), Leber *et al.* reported a sensitivity of 77% and 82% using EBCT and MSCT, respectively.[34] Specificity was also comparable – 93% for EBCT and 96% for MSCT. There were significant differences between EBCT and MSCT in two areas; contrast-to-noise ratio and number of assessable coronary segments, with MSCT performing marginally better in each. Despite the study being restricted to the proximal two-thirds of the coronary tree, only 76% of EBCT and 82% of MSCT vessel segments could be evaluated, the remainder being excluded mainly because of motion artefacts or poor contrast-to-noise ratio. Of note, in their largest series of EBCT angiography studied, Achenbach *et al.* could only evaluate 75% of studied vessel segments, excluding particularly the fast-moving right coronary and circumflex vessels.[33]

Such difficulty in visualising all the coronary segments reliably is in fact common to almost all clinical studies investigating non-invasive coronary imaging and, although understandable, such practice does tend to give a misleading accuracy to the results. Nevertheless, all studies have consistently reported high NPV (95% to 98%) to rule out significant coronary stenosis in those segments evaluable.

Uniformity and imaging standards are fair among EBCT studies. The imaging procedures used by the above studies were all performed with similar imaging techniques. The studies were performed with a C-100 or C-150XLP EBCT scanner (Imatron). The ECG triggering was employed so that each image was obtained at the same point in diastole. However, it should be noted that all studies published so far have been performed on EBCT scanners with technical capabilities below the current standard. In addition, all studies that have been published have used acquisition of 3.0-mm slices, not 1.5-mm slices. The recent introduction of the new e-speed scanner (GE-Imatron) allows for image acquisition in 50 ms, as well as obtaining dual imaging and allowing thinner slices with less cardiac motion. The clinical effects of these improvements remain to be investigated.

Limitations

The EBCT coronary angiographic studies had a technical success rate of 85 to 100%; 8 to 25% of coronary arteries were non-assessable. Both EBCT and MSCT share the same technical limitations due especially to severe vessel calcification, coronary motion artefact, trigger artefact due to arrhythmia, and metallic structures such as surgical clips or stents. Recent studies have demonstrated that ECG triggering at approximately 40% instead of 80% of the R-R interval (early diastole or end-systole) causes less coronary motion and might significantly improve imaging.[35,36]

COPYRIGHT MEDINEWS
CARDIOLOGY LIMITED
REPRODUCTION PROHIBITED

Radiation exposure of computer tomography

The radiation exposure for MSCT with retrospective ECG gating has been calculated to be between 3.9 and 6.2 mSv. This is currently about twice as high as for conventional selective diagnostic ICA (2 to 3 mSv). With retrospective gating, radiation is applied continuously during the entire heart cycle, though only data acquired during diastole are used for image reconstruction. The radiation exposure can be reduced with prospective gating technique, estimated at 0.8 to 1.5 mSv with 4- to 16-slice MSCT. Using EBCT coronary angiography with prospective triggering, the effective radiation doses are 1.5 and 2.0 mSv for male and female patients, respectively. The typical radiation dose for calcium scanning using EBCT is 0.5 to 0.7 mSv. For both EBCT and MSCT, the radiation dose increases with thinner slices and more overlapping images. In female patients, the effective radiation dose is about 25% higher than in male patients. Certainly, depending on the operator and the nature of the diagnostic procedure, the effective dose of X-ray-based coronary angiography can be significantly higher. Although the long-term risks associated with this level of radiation exposure are relatively low, it raises a concern about repeated use or use in younger individuals and women of childbearing age.

Current clinical value of non-invasive coronary angiography

Looking at the evidence thus far, image quality currently is not robust enough to consider non-invasive coronary angiography by CMRA, MSCT or EBCT an alternative to conventional ICA for the detection of native coronary artery stenosis in all patients. All three techniques, however, are currently used clinically in certain centres. Current data support the use of these methods in select-

Panting pp AIC49-AIC56:Panting pp AIC49-AIC56 4/8/06 4:56 pm Page 7

Key messages

- There is growing interest in non-invasive technologies to diagnose obstructive coronary artery disease
- The three most promising modalities are coronary magnetic resonance angiography (CMRA), multi-slice spiral chemical computed tomography (MSCT) and electron-beam computed tomography (EBCT)
- Possible indications include ruling out flow-limiting stenosis and early detection of obstructive coronary artery disease

ed patients and when carefully performed to exclude the presence of significant stenosis in the proximal and mid-portions of the coronary artery. This may be adequate for some patients, as the decision regarding revascularisation therapy of CAD frequently relies on the presence of proximal stenosis. The latest range of MSCT, with its superior resolution to CMRA and EBCT, can be used to analyse most vessels, including those < 1.5 mm in diameter in distal segments or side branches.

These imaging modalities have already been successful in the detection of coronary artery anomalies, and stenosis in the body of coronary bypass grafts.[37,38] However, the high NPV (consistently > 97%) of most clinical studies suggests an important role of non-invasive angiography for reliably ruling out significant flow-limiting stenosis in patients with an equivocal clinical presentation such as atypical chest pain, inconclusive stress tests or those unable to undergo stress tests, who might otherwise be referred for invasive cardiac catheterisation. Others may include patients with low to intermediate pre-test probability of disease and those with high cardiovascular risk factors referred for early detection of obstructive CAD. It should be noted that the results of these studies may not be extrapolated from their intermediate- to high-risk patients group to a low-risk population. Diagnostic tests will not perform as well when extended to populations with low disease prevalence; inevitably, higher rates of false-positive results will occur.

Nevertheless, the list of indications for non-invasive coronary angiography is evolving as the diagnostic quality is rapidly improving. With the continuous improvements in the capabilities of these technologies that we have witnessed in recent years, there is little question that non-invasive coronary angiography will become a clinical reality, changing the workup of patients suspected of having obstructive CAD and the follow-up after surgical and percutaneous revascularisation.[16] There is considerable training and practice involved in developing the skills necessary to convert raw information from these imaging modalities to optimal diagnostic images[15] but these imaging modalities will provide important diagnostic information in a faster, less expensive, more patient-friendly and safer manner than conventional coronary angiography.

COPYRIGHT MEDINEWS (CARDIOLOGY) LIMITED REPRODUCTION PROHIBITED

Conflict of interest

None declared.

References

1. Manning WJ, Li W, Edelman RR. A preliminary report comparing magnetic resonance coronary angiography with conventional angiography. *N Engl J Med* 1993;**328**:828-32.
2. Post JC, van Rossum AC, Hofman MB, de Cock CC, Valk J, Visser CA. Clinical utility of two-dimensional magnetic resonance angiography in detecting coronary artery disease. *Eur Heart J* 1997;**18**:426-33.
3. Kim WY, Danias PG, Stuber M *et al*. Coronary magnetic resonance angiography for the detection of coronary stenoses. *N Engl J Med* 2001;**345**:1863-9.
4. Sommer T, Hofer U, Hackenbroch M *et al*. [Submillimeter 3D coronary MR angiography with real-time navigator correction in 107 patients with suspected coronary artery disease]. *Rofo* 2002;**174**:459-66.
5. Plein S, Ridgway JP, Jones TR, Bloomer TN, Sivananthan MU. Coronary artery disease: assessment with a comprehensive MR imaging protocol – initial results. *Radiology* 2002;**225**:300-07.
6. Regenfus M, Ropers D, Achenbach S *et al*. Diagnostic value of maximum intensity projections versus source images for assessment of contrast-enhanced three-dimensional breath-hold magnetic resonance coronary angiography. *Invest Radiol* 2003;**38**:200-06.
7. van Geuns RJ, Wielopolski PA, de Bruin HG *et al*. MR coronary angiography with breath-hold targeted volumes: preliminary clinical results. *Radiology* 2000;**217**:270-7.
8. Yang PC, Meyer CH, Terashima M *et al*. Spiral magnetic resonance coronary angiography with rapid real-time localization. *J Am Coll Cardiol* 2003;**41**:1134-41.
9. Regenfus M, Ropers D, Achenbach S *et al*. Noninvasive detection of coronary artery stenosis using contrast-enhanced three-dimensional breath-hold magnetic resonance coronary angiography. *J Am Coll Cardiol* 2000;**36**:44-50.
10. Jahnke C, Paetsch I, Nehrke K *et al*. Rapid and complete coronary arterial tree visualization with magnetic resonance imaging: feasibility and diagnostic performance. *Eur Heart J* 2005;**26**:2313-19.
11. Danias PG, Roussakis A, Ioannidis JP. Diagnostic performance of coronary magnetic resonance angiography as compared against conventional X-ray angiography: a meta-analysis. *J Am Coll Cardiol* 2004;**44**:1867-76.
12. Gibbons RJ, Araoz PA. The year in cardiac imaging. *J Am Coll Cardiol* 2005;**46**:542-51.
13. Fuster V, Kim RJ. Frontiers in cardiovascular magnetic resonance. *Circulation* 2005;**112**:135-44.
14. Fuster V, Fayad ZA, Moreno PR, Poon M, Corti R, Badimon JJ. Atherothrombosis and high-risk plaque: Part II: approaches by noninvasive computed tomographic/magnetic resonance imaging. *J Am Coll Cardiol* 2005;**46**:1209-18.
15. Budoff MJ, Cohen MC, Garcia MJ *et al*. ACCF/AHA clinical competence statement on cardiac imaging with computed tomography and magnetic resonance: a report of the American College of Cardiology Foundation/American Heart Association/American College of Physicians Task Force on Clinical Competence and Training. *J Am Coll Cardiol* 2005;**46**:383-402.
16. Schmermund A, Erbel R. Non-invasive computed tomographic coronary angiography: the end of the beginning. *Eur Heart J* 2005;**26**:1451-3.
17. Budoff MJ. Noninvasive coronary angiography using computed tomography. *Expert Rev Cardiovasc Ther* 2005;**3**:123-32.
18. Mochizuki T, Murase K, Koyama Y, Higashino H, Ikezoe J. LAD stenosis detected by subsecond spiral CT. *Circulation* 1999;**99**:1523.
19. Achenbach S, Giesler T, Ropers D *et al*. Detection of coronary artery stenoses by contrast-enhanced, retrospectively electrocardiographically-gated, multislice spiral computed tomography. *Circulation* 2001;**103**:2535-8.
20. Knez A, Becker CR, Leber A *et al*. Usefulness of multislice spiral computed tomography angiography for determination of coronary artery stenoses. *Am J Cardiol* 2001;**88**:1191-4.
21. Nieman K, Oudkerk M, Rensing BJ *et al*. Coronary angiography with multi-slice computed tomography. *Lancet* 2001;**357**:599-603.
22. Nieman K, Cademartiri F, Lemos PA, Raaijmakers R, Pattynama PM, de

Panting pp AIC49-AIC56:Panting pp AIC49-AIC56 4/8/06 4:56 pm Page 8

Feyter PJ. Reliable noninvasive coronary angiography with fast submillimeter multislice spiral computed tomography. *Circulation* 2002;**106**:2051-4.

23. Achenbach S, Ropers D, Pohle FK *et al*. Detection of coronary artery stenoses using multi-detector CT with 16 x 0.75 collimation and 375 ms rotation. *Eur Heart J* 2005;**26**:1978-86.
24. Leschka S, Alkadhi H, Plass A *et al*. Accuracy of MSCT coronary angiography with 64-slice technology: first experience. *Eur Heart J* 2005;**26**:1482-7.
25. Raff GL, Gallagher MJ, O'Neill WW, Goldstein JA. Diagnostic accuracy of noninvasive coronary angiography using 64-slice spiral computed tomography. *J Am Coll Cardiol* 2005;**46**:552-7.
26. Martuscelli E, Romagnoli A, D'Eliseo A *et al*. Accuracy of thin-slice computed tomography in the detection of coronary stenoses. *Eur Heart J* 2004;**25**:1043-8.
27. Kuettner A, Kopp AF, Schroeder S *et al*. Diagnostic accuracy of multidetector computed tomography coronary angiography in patients with angiographically proven coronary artery disease. *J Am Coll Cardiol* 2004;**43**:831-9.
28. Kuettner A, Beck T, Drosch T *et al*. Image quality and diagnostic accuracy of non-invasive coronary imaging with 16 detector slice spiral computed tomography with 188 ms temporal resolution. *Heart* 2005;**91**:938-41.
29. Hoffmann U, Moselewski F, Cury RC *et al*. Predictive value of 16-slice multidetector spiral computed tomography to detect significant obstructive coronary artery disease in patients at high risk for coronary artery disease: patient-versus segment-based analysis. *Circulation* 2004;**110**:2638-43.
30. Schuijf JD, Bax JJ, Salm LP *et al*. Noninvasive coronary imaging and assessment of left ventricular function using 16-slice computed tomography. *Am J Cardiol* 2005;**95**:571-4.
31. Mollet NR, Cademartiri F, van Mieghem CA *et al*. High-resolution spiral computed tomography coronary angiography in patients referred for diagnostic conventional coronary angiography. *Circulation* 2005;**112**:2318-23.
32. Kefer J, Coche E, Legros G *et al*. Head-to-head comparison of three-dimensional navigator-gated magnetic resonance imaging and 16-slice computed tomography to detect coronary artery stenosis in patients. *J Am Coll Cardiol* 2005;**46**(1):92-100.
33. Achenbach S, Moshage W, Ropers D, Nossen J, Daniel WG. Value of electron-beam computed tomography for the noninvasive detection of high-grade coronary-artery stenoses and occlusions. *N Engl J Med* 1998;**339**:1964-71.
34. Leber AW, Knez A, Becker C *et al*. Non-invasive intravenous coronary angiography using electron beam tomography and multislice computed tomography. Heart 2003;**89**:633-9.
35. Lu B, Mao SS, Zhuang N, Bakhsheshi H *et al*. Coronary artery motion during the cardiac cycle and optimal ECG triggering for coronary artery imaging. *Invest Radiol* 2001;**36**:250-6.
36. Achenbach S, Ropers D, Holle J, Muschiol G, Daniel WG, Moshage W. In-plane coronary arterial motion velocity: measurement with electron-beam CT. *Radiology* 2000;**216**:457-63.
37. Langerak SE, Vliegen HW, Jukema JW *et al*. Value of magnetic resonance imaging for the noninvasive detection of stenosis in coronary artery bypass grafts and recipient coronary arteries. *Circulation* 2003;**107**:1502-08.
38. Achenbach S, Moshage W, Ropers D, Nossen J, Bachmann K. Noninvasive, three-dimensional visualization of coronary artery bypass grafts by electron beam tomography. *Am J Cardiol* 1997;**79**:856-61.
39. Pennell DJ, Bogren HG, Keegan J, Firmin DN, Underwood SR. Assessment of coronary artery stenosis by magnetic resonance imaging. *Heart* 1996;**75**:127-33.
40. Kessler W, Achenbach S, Moshage W *et al*. Usefulness of respiratory gated magnetic resonance coronary angiography in assessing narrowings ≥ 50% in diameter in native coronary arteries and in aortocoronary bypass conduits. *Am J Cardiol* 1997;**80**:989-93.
41. Muller MF, Fleisch M, Kroeker R, Chatterjee T, Meier B, Vock P. Proximal coronary artery stenosis: three-dimensional MRI with fat saturation and navigator echo. *J Magn Reson Imaging* 1997;**7**:644-51.
42. van Geuns RJ, de Bruin HG, Rensing BJ *et al*. Magnetic resonance imaging of the coronary arteries: clinical results from three dimensional evaluation of a respiratory gated technique. *Heart* 1999;**82**:515-19.
43. Sandstede JJ, Pabst T, Beer M *et al*. Three-dimensional MR coronary angiography using the navigator technique compared with conventional coronary angiography. *AJR Am J Roentgenol* 1999;**172**:135-9.
44. Sardanelli F, Molinari G, Zandrino F, Balbi M. Three-dimensional, navigator-echo MR coronary angiography in detecting stenoses of the major epicardial vessels, with conventional coronary angiography as the standard of reference. *Radiology* 2000;**214**:808-14.
45. Nikolaou K, Huber A, Knez A, Scheidler J, Petsch R, Reiser M. Navigator echo-based respiratory gating for three-dimensional MR coronary angiography: reduction of scan time using a slice interpolation technique. *J Comput Assist Tomogr* 2001;**25**:378-87.
46. Ropers D, Baum U, Pohle K *et al*. Detection of coronary artery stenoses with thin-slice multi-detector row spiral computed tomography and multiplanar reconstruction. *Circulation* 2003;**107**:664-6.
47. Mollet NR, Cademartiri F, Nieman K *et al*. Multislice spiral computed tomography coronary angiography in patients with stable angina pectoris. *J Am Coll Cardiol* 2004;**43**:2265-70.
48. Mollet NR, Cademartiri F, Krestin GP *et al*. Improved diagnostic accuracy with 16-row multi-slice computed tomography coronary angiography. *J Am Coll Cardiol* 2005;**45**:128-32.
49. Hoffmann MH, Shi H, Schmitz BL *et al*. Noninvasive coronary angiography with multislice computed tomography. *JAMA* 2005;**293**:2471-8.
50. Nakanishi T, Ito K, Imazu M, Yamakido M. Evaluation of coronary artery stenoses using electron-beam CT and multiplanar reformation. *J Comput Assist Tomogr* 1997;**21**:121-7.
51. Schmermund A, Rensing BJ, Sheedy PF, Bell MR, Rumberger JA. Intravenous electron-beam computed tomographic coronary angiography for segmental analysis of coronary artery stenoses. *J Am Coll Cardiol* 1998;**31**:1547-54.
52. Reddy GP, Chernoff DM, Adams JR, Higgins CB. Coronary artery stenoses: assessment with contrast-enhanced electron-beam CT and axial reconstructions. *Radiology* 1998;**208**:167-72.
53. Budoff MJ, Oudiz RJ, Zalace CP *et al*. Intravenous three-dimensional coronary angiography using contrast enhanced electron beam computed tomography. *Am J Cardiol* 1999;**83**:840-5.
54. Rensing BJ, Bongaerts A, van Geuns RJ, van Ooijen P, Oudkerk M, de Feyter PJ. Intravenous coronary angiography by electron beam computed tomography: a clinical evaluation. *Circulation* 1998;**98**:2509-12.
55. Achenbach S, Ropers D, Regenfus M, Muschiol G, Daniel WG, Moshage W. Contrast enhanced electron beam computed tomography to analyse the coronary arteries in patients after acute myocardial infarction. *Heart* 2000;**84**:489-93.
56. Leber AW, Knez A, Mukherjee R *et al*. Usefulness of calcium scoring using electron beam computed tomography and noninvasive coronary angiography in patients with suspected coronary artery disease. *Am J Cardiol* 2001;**88**:219-23.
57. Ropers D, Regenfus M, Stilianakis N *et al*. A direct comparison of noninvasive coronary angiography by electron beam tomography and navigator-echo-based magnetic resonance imaging for the detection of restenosis following coronary angioplasty. *Invest Radiol* 2002;**37**:386-92.
58. Nikolaou K, Huber A, Knez A, Becker C, Bruening R, Reiser M. Intraindividual comparison of contrast-enhanced electron-beam computed tomography and navigator-echo-based magnetic resonance imaging for noninvasive coronary artery angiography. *Eur Radiol* 2002;**12**:1663-71.

COPYRIGHT MEDINEWS (CARDIOLOGY) LIMITED REPRODUCTION PROHIBITED