SPECIAL ARTICLE

Cardiac computed tomography: indications, applications, limitations, and training requirements

Report of a Writing Group deployed by the Working Group Nuclear Cardiology and Cardiac CT of the European Society of Cardiology and the European Council of Nuclear Cardiology

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As a consequence of improved technology, there is growing clinical interest in the use of multi-detector row computed tomography (MDCT) for non-invasive coronary angiography. Indeed, the accuracy of MDCT to detect or exclude coronary artery stenoses has been high in many published studies. This report of a Writing Group deployed by the Working Group Nuclear Cardiology and Cardiac CT (WG 5) of the European Society of Cardiology and the European Council of Nuclear Cardiology summarizes the present state of cardiac CT technology, as well as the currently available data concerning its accuracy and applicability in certain clinical situations. Besides coronary CT angiography, the use of CT for the assessment of cardiac morphology and function, evaluation of perfusion and viability, and analysis of heart valves is discussed. In addition, recommendations for clinical applications of cardiac CT imaging are given and limitations of the technique are described.

Introduction

The introduction of multi-detector row computed tomography (MDCT) in 1999 led to a significant improvement in the temporal and spatial resolution of CT, which permitted substantial expansion of potential indications for CT imaging. Small and rapidly moving anatomic structures could be visualized with good image quality, and early experience with the initial four-slice scanners demonstrated the potential of MDCT to visualize the coronary arteries.

The possibility to perform cardiac and coronary imaging was a major driving force behind an ongoing, rapid evolution of scanner technology, accompanied by improvements of software

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and post-processing tools. The most recent generations of MDCT with the ability to acquire 64 slices simultaneously allow relatively robust morphological and functional imaging of the heart. Although initially, clinical applications were restricted to the detection of coronary calcium, visualization of the coronary artery lumen (non-invasive coronary angiography) has now become the major focus of cardiac MDCT. In addition, the assessment of non-stenotic coronary atherosclerotic plaques, coronary stents, or bypass grafts has become possible in selected situations, as well as the evaluation of left and right ventricular function, valvular function, coronary and pulmonary veins, and general morphology of the heart and great vessels.

The present manuscript summarizes the current state of technology and clinical applications of cardiac CT, with a special emphasis on coronary CT angiography. It does not constitute a meta-analysis of published literature, but merely reflects an expert consensus on the current status and limitations of cardiac CT imaging, as well as potential clinical indications.

Technical background and data acquisition

The first commercially available CT technology that allowed ECG-gated cardiac CT imaging was electron beam CT (EBCT), which had been used for non-invasive coronary imaging since the early 1990s.[1] The system provided a very high temporal resolution (100 ms per image), but had substantial limitations concerning spatial resolution and image noise, which negatively affected image quality.[2]

The introduction of MDCT[3,4] provided the technical requirements to perform cardiac imaging with CT systems that followed the traditional design of a rotating X-ray tube and detectors.[5] Multiple detector rows permit high-resolution imaging with short overall data acquisition time, and the increased gantry rotation speed, together with dedicated ECG-gated image reconstruction algorithms, provides for high temporal resolution and the ability to obtain phase-correlated image data sets. ECG-gated four-slice MDCT, introduced around the year 2000,[6–8] provided the first evidence that mechanical CT scanning of the heart and coronary arteries is feasible, but was burdened with a high rate of unevaluable studies, mostly due to insufficient temporal resolution. Currently, 64-slice CT is considered state-of-the-art for cardiac CT imaging, whereas 256-slice systems are being developed.

Although 'sequential' imaging (so-called 'step-and-shoot' mode) is used in some instances, cardiac CT is usually based on continuous spiral scanning of the heart with a very low pitch (table feed/gantry rotation) in order to achieve oversampling of information across different phases of the cardiac cycle and in some cases even across several consecutive cardiac cycles. Simultaneous recording of the ECG permits retrospective reconstruction of images at any desired phase of the cardiac cycle, which in turn provides for the identification of the time instant in which the cardiac structures show the least residual motion. In addition, the ability to reconstruct data sets at multiple time instants during the cardiac cycle allows for 'dynamic' imaging and analysis of function.

Coronary artery visualization requires the acquisition of CT data with the highest temporal and spatial resolution. With current 64-slice CT systems, data acquisition is performed within a single breath-hold of about 5–10 s. Synchronization of data acquisition and contrast enhancement can be achieved by calculating the veno-arterial transit time, using a small bolus of contrast agent and retrospective analysis of the enhancement pattern over time (so-called 'test bolus' technique), or by real-time monitoring of the arrival of the bolus, for example, in the ascending aorta (so-called 'bolus tracking' technique). Typically, the amount of contrast material required for coronary CT angiography is about 60–100 mL depending on scanner type, patient size, heart rate, and body mass index. The contrast agent should be of high iodine concentration. Usually, the flow rate is 5 mL/s, but especially in obese patients, increasing the flow rate may be advantageous.

After acquisition of the raw data, retrospectively ECG-gated image data sets are generated. These data sets usually consist of 200–300 thin (0.5–0.75 mm) and overlapping slices in transaxial orientation. Especially for coronary artery imaging, it is important to carefully identify the time instant in the cardiac cycle which shows least cardiac motion. For lower heart rates, the best time instant is usually in the mid- to end-diastolic phase, whereas for higher heart rates, reconstruction in end-systole may yield superior results.[9–11] The average heart rate and heart rate variability have been shown to substantially influence image quality. As the most important predictor for diagnostic image quality, low (<60 b.p.m.) and regular heart rates ($\Delta HR < \pm 2$ b.p.m.) have been identified.[12–16] For this reason, beta blockers are frequently administered prior to the CT scan in order to lower heart rate and to obtain robust image quality.[17] Nitroglycerin can be administered sublingually to achieve vasodilatation with optimal opacification and visualization of the coronary arteries.[18]

Radiation exposure

The effective radiation dose of a contrast-enhanced cardiac CT scan is ∼5–20 mSv.[19–33] Numerous factors influence radiation dose. Reductions in radiation dose can be achieved by obvious and straightforward measures, such as keeping the length of the scan volume as short and tube current as low as possible. Another effective way of reducing radiation dose is the use of ECG-correlated tube current modulation,[34] in which full tube current is limited to a short-time period in diastole, resulting in the reduction of radiation dose by 30–40%.[35] Tube current modulation is particularly effective in low heart rates. Furthermore, reducing tube voltage to 100 kV instead of the commonly used 120 kV results in a substantial further reduction of radiation exposure[36] and should be considered in patients with a low-to-moderate body mass. Recently, an image-acquisition protocol using a 'step-and-shoot' approach has been introduced for coronary artery imaging by MDCT. This is a non-spiral mode, with the table remaining stationary while the X-ray tube rotates around the patient. When data acquisition is completed for one location, the table is advanced to the next location for the subsequent scan. Initial reports indicate substantial reductions in radiation dose.[37]

While the radiation dose of a cardiac CT scan is in the same order of magnitude as other diagnostic tests used in cardiology,

such as nuclear perfusion scans (with a typical dose of 8–25 mSv[38,39]), all possible measures should be taken to keep the dose as low as possible, and considerations as to clinical indications for cardiac CT must always take radiation exposure into account.[39,40]

Coronary artery imaging

Detection of coronary artery stenoses

The opportunity to non-invasively visualize coronary anatomy is the major reason for the current interest in cardiac MDCT. In the year 2000, four-slice CT systems, for the first time, allowed coronary artery imaging with spiral CT, but limited spatial and temporal resolution, as well as long scan times (up to 35 s) limited their clinical value for coronary artery visualization. Only the proximal parts of the coronary arteries were interpretable, and up to 25% of coronary segments could not be evaluated due to insufficient image quality.[6,8] With the introduction of 16- and 64-slice MDCT systems, improved temporal and spatial resolution as well as substantially shorter scan times led to improved image quality throughout the entire coronary tree[41](Figure 1). A recent meta-analysis demonstrated a significant improvement in the accuracy for the detection of coronary artery stenoses for 64-slice CT when compared with previous scanner generations. The weighted mean sensitivity for the detection of coronary artery stenoses increased from 84% for four-slice CT and 83% for 16-slice CT to 93% for 64-slice CT, whereas the respective specificities were 93, 96, and 96%.[42]

The results of recent studies that analysed the accuracy of 64-slice CT and dual-source CT for the detection of coronary artery stenoses in patients with suspected coronary artery disease (CAD) are summarized in Tables 1 and 2.[43–53] Pooling the data of more than 800 patients yields a sensitivity of 89% (95% CI 87–90) with a specificity of 96% (95% CI 96–97) and a positive and negative predictive value of 78% (95% CI 76–80) and 98% (95% CI 98–99), respectively. On average, 4.5% of segments (mainly distal segments or very small side branches) could not be evaluated. Importantly, the negative predictive value was consistently high in all studies, indicating that the technique may
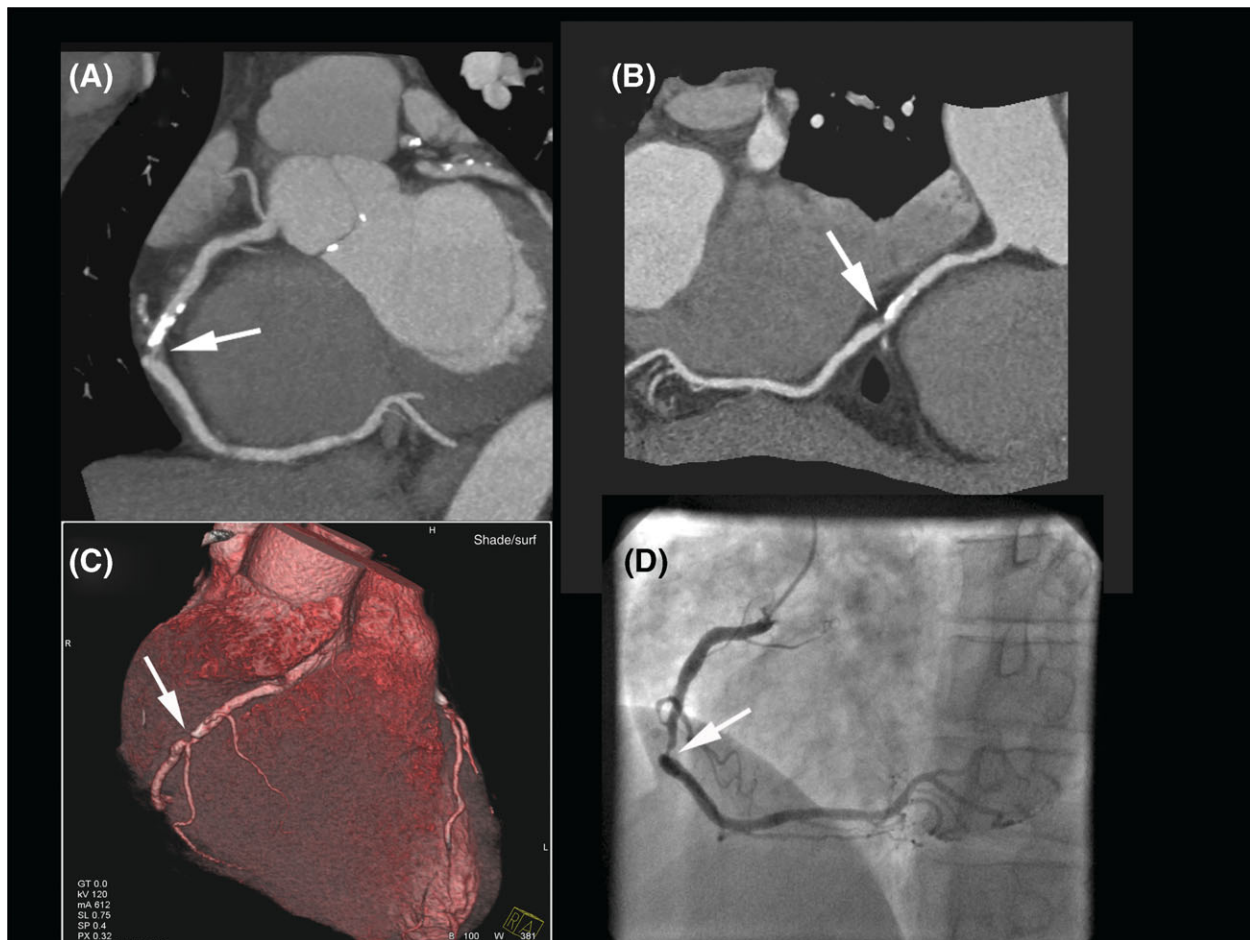

Figure 1 Coronary artery stenosis detection with multi-detector row computed tomography. High-grade stenosis of the mid-right coronary artery in a 55-year-old man with atypical chest pain. (A) A maximum intensity projection, with a high-grade luminal reduction distal to a calcified segment. (B) A curved multiplanar reconstruction. (C) A three-dimensional rendering of the heart and right coronary artery. (D) shows the corresponding coronary angiogram.

Table 1 Diagnostic performance of 64-slice computed tomography and dual-source computed tomography for the detection of significant coronary stenosis (luminal diameter >50%) on a per-segment basis

Author	Number of patients	Not evaluable (%)	Sensitivity (%)	Specificity (%)	PPV (%)	NPV (%)
Leschka *et al.*[53]	67	0 (0/1005)	94 (165/176)	97 (805/829)	87 (165/189)	99 (805/816)
Leber *et al.*[44]	55	0 (0/732)	76 (57/75)	97 (638/657)	75 (57/76)	97 (638/656)
Raff *et al.*[49]	70	12 (130/1065)	86 (79/92)	95 (802/843)	66 (79/120)	98 (802/815)
Mollet *et al.*[46]	51	0 (0/725)	99 (93/94)	95 (601/631)	76 (93/123)	99 (601/602)
Ropers *et al.*[50]	81	4 (45/1128)	93 (39/42)	97 (1010/1041)	56 (39/70)	100 (1010/1013)
Schuijf *et al.*[51]	60	1.4 (12/854)	85 (62/73)	98 (755/769)	82 (62/76)	99 (755/766)
Ong *et al.*[48]	134	9.7 (143/1474)	82 (177/217)	96 (1067/1114)	79 (177/224)	96 (1067/1107)
Ehara *et al.*[43]	69	8 (82/966)	90 (275/304)	94 (545/580)	89 (275/310)	95 (545/574)
Nikolaou *et al.*[47]	72	9.5 (97/1020)	82 (97/118)	95 (762/805)	69 (97/140)	97 (762/789)
Weustink *et al.*[52]	77	0 (0/1489)	95 (208/220)	95 (1200/1269)	75 (208/277)	99 (1200/1212)
Leber *et al.*[45]	88	1.3 (16/1232)	94 (38/42)	99 (1165/1174)	81 (38/47)	99 (1165/1169)
Total	824	4.5 (525/11690) (95% CI 4.1−4.9)	89 (1290/1453) (95% CI 87−90)	96 (9350/9712) (95% CI 96−97)	78 (1290/1652) (95% CI 76−80)	98 (6350/9513) (95% CI 98−99)

All values are expressed as per cent with absolute numbers in parentheses. Sensitivity and specificity were calculated only for evaluable segments.
95% CI, 95% confidence interval; NPV, negative predictive value; PPV, positive predictive value.

Table 2 Diagnostic performance of 64-slice computed tomography and dual-source computed tomography for the detection of significant coronary stenosis (luminal diameter >50%) on a per-patient basis

Author	Number of patients	Not evaluable (%)	Sensitivity (%)	Specificity (%)	PPV (%)	NPV (%)
Leschka *et al.*[53]	67	0	100 (47/47)	100 (20/20)	100 (47/47)	100 (20/20)
Leber *et al.*[44]	59[a]	23.7 (14/59)	88 (22/25)	85 (17/20)	88 (22/25)	85 (17/20)
Raff *et al.*[49]	70	0	95 (38/40)	90 (27/30)	93 (38/41)	93 (27/29)
Mollet *et al.*[46]	52	1.9 (1/52)	100 (38/38)	92 (12/13)	97 (38/39)	100 (12/12)
Ropers *et al.*[50]	84	3.6 (3/84)	96 (25/26)	91 (50/55)	83 (25/30)	98 (50/51)
Schuijf *et al.*[51]	61	1.6 (1/61)	94 (29/31)	97 (28/29)	97 (29/30)	93 (27/29)
Ehara *et al.*[43]	69	2.9 (2/69)	98 (59/60)	86 (6/7)	98 (59/60)	86 (6/7)
Nikolaou *et al.*[47]	72	5.6 (4/72)	97 (38/39)	79 (23/29)	86 (38/44)	96 (23/24)
Weustink *et al.*[52]	77	0	99 (76/77)	87 (20/23)	96 (76/79)	95 (20/21)
Leber *et al.*[45]	90	2.2 (2/90)	95 (20/21)	90 (60/67)	74 (20/27)	99 (60/61)
Total	701	3.8 (27/701) (95% CI 2.6−5.6)	98 (394/404) (95% CI 95−99)	90 (263/293) (95% CI 86−93]	93 (394/424) (95% CI 90−95)	95 (263/273) (95% CI 93−98)

All values are expressed as per cent with absolute numbers in parentheses.
95% CI, 95% confidence interval; NPV, negative predictive value; PPV, positive predictive value.
[a]Exclusion of patients with stents.

be most suitable as a non-invasive tool to rule out significant CAD and avoid further imaging or invasive angiography.

However, it is important to realize that patient selection may still heavily influence results, with substantially impaired image quality in patients with higher heart rates or arrhythmias.[15] Image quality may also be degraded in patients with severe CAD due to the presence of extensive calcifications which potentially limit precise assessment of the stenosis severity.[48] Improvements can be expected from the introduction of dual-source CT systems,[54] which provide higher temporal resolution by employing two rotating X-ray tubes rather than one.[55] Preliminary studies using this technique showed that

up to 98% of all coronary segments could be visualized without motion artefacts, even without lowering the heart rate by administration of beta blockers.[10,45,56] Moreover, even in patients without stable sinus rhythm, a high accuracy could be obtained, and an initial, small study reported a high accuracy for stenosis detection in patients with advanced CAD.[57] In addition, 256-slice MDCT systems, whose large coverage along the *z*-axis (patient's longitudinal axis) may allow imaging of the entire heart in a single cardiac cycle and will make coronary CT angiography less susceptible to arrhythmias or heart rate variability, will become available in the near future.[58]

Lesion severity and functional relevance

The limited temporal and spatial resolution of CT may create diffi-culties in accurately assessing the severity of coronary artery ste-noses. There is a tendency to overestimate the degree of luminal narrowing by CT when compared with invasive angiography,[59] and pronounced calcification of a vessel segment can make lesion assessment particularly difficult. Usually, calcification will lead to overestimation, rather than underestimation of lesion severity.[60] Furthermore, coronary CT angiography is limited to the anatomic visualization of stenoses and does not provide information as to the functional relevance of a lesion. In a recent head-to-head com-parison of MDCT and nuclear myocardial perfusion imaging with SPECT in 114 patients with intermediate likelihood of CAD,[61] only 45% of patients with an abnormal MDCT had abnormal per-fusion on SPECT. Even in patients with obstructive lesions on MDCT, 50% still had a normal SPECT. These findings are in agree-ment with other preliminary reports[62–64] which showed that only a fraction of patients with obstructive coronary lesions demonstrate ischaemia on SPECT and positron emission tomography (PET) per-fusion imaging. For this reason, although 64-slice MDCT is a reliable tool to rule out functionally relevant CAD in a non-selected popu-lation with an intermediate pre-test likelihood of disease, an abnor-mal coronary CT angiogram does not necessarily predict ischaemia. In fact, since coronary CT angiography and perfusion imaging provide different and complementary information, their sequential use or hybrid imaging may provide useful incremental information (*Figure 2*). In a recent study, hybrid PET/CT[65] was evaluated in patients with suspected CAD, which yielded a sensitivity and speci-ficity of 90 and 98%, respectively, for the detection of haemodyna-mically relevant coronary lesions. Rispler *et al.*[66] compared an experimental SPECT/MDCT hybrid imaging device for the assess-ment of coronary anatomy and myocardial perfusion in 56 patients with angina pectoris. The ability of fused SPECT/MDCT images to diagnose physiologically significant lesions showing >50% stenosis
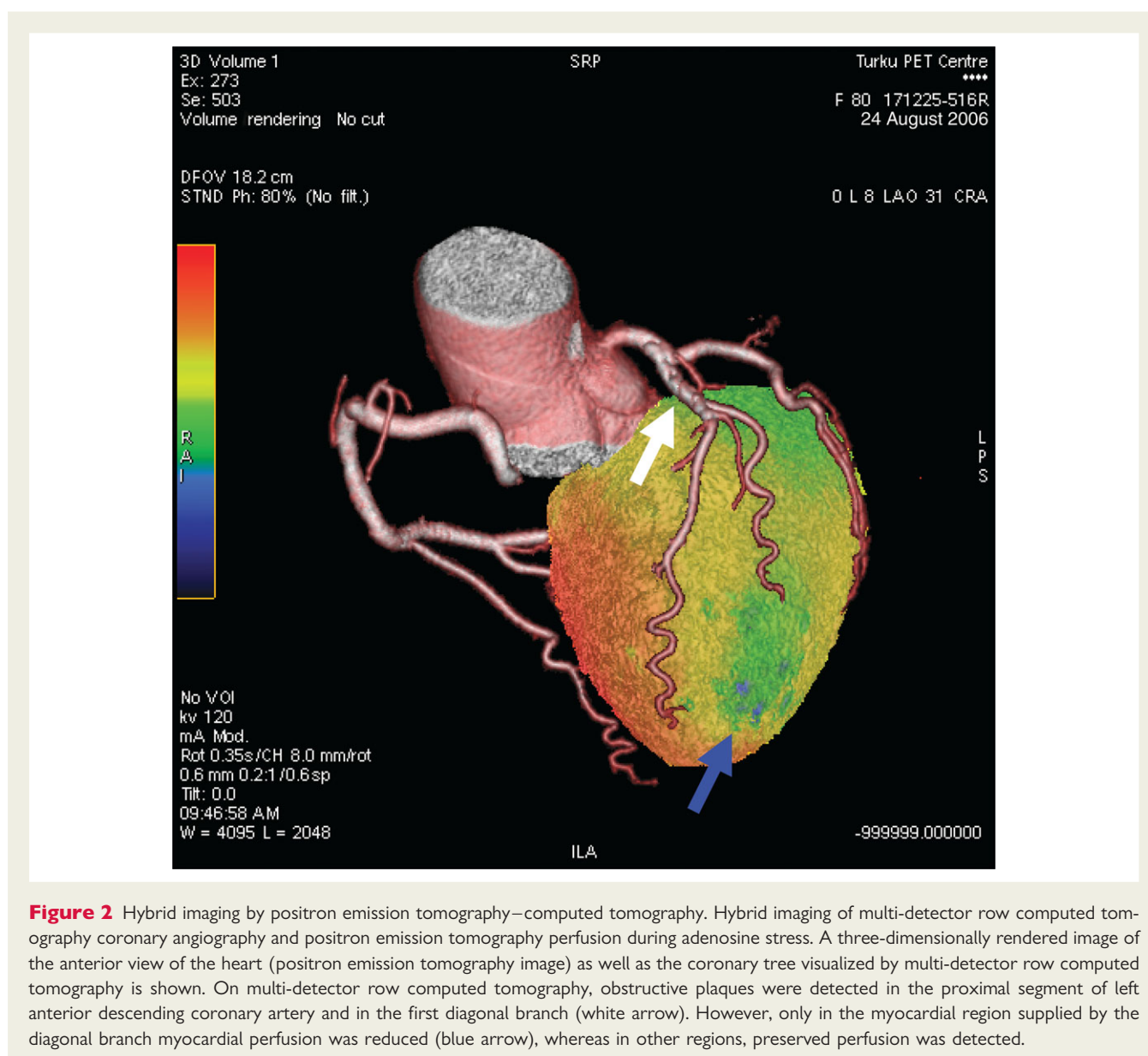

Figure 2 Hybrid imaging by positron emission tomography–computed tomography. Hybrid imaging of multi-detector row computed tom-ography coronary angiography and positron emission tomography perfusion during adenosine stress. A three-dimensionally rendered image of the anterior view of the heart (positron emission tomography image) as well as the coronary tree visualized by multi-detector row computed tomography is shown. On multi-detector row computed tomography, obstructive plaques were detected in the proximal segment of left anterior descending coronary artery and in the first diagonal branch (white arrow). However, only in the myocardial region supplied by the diagonal branch myocardial perfusion was reduced (blue arrow), whereas in other regions, preserved perfusion was detected.

and reversible perfusion defects in the same territory was determined and compared with stand-alone MDCT. The sensitivity, specificity, positive predictive and negative predictive values for MDCT were 96, 63, 31, and 99%, respectively, compared with 96, 95, 77, and 99%, respectively, for the combined SPECT/MDCT examination. The authors concluded that hybrid imaging led to an improvement of diagnostic accuracy.

Clinical implications and recommendations

Most of the accuracy data that are currently available concerning the detection of coronary stenoses by CT angiography have been obtained in patient groups with suspected CAD and stable symptoms. The consistently high negative predictive value in all studies suggests that CT angiography will be clinically useful to rule out coronary stenoses in this patient group. In patients with a very high pre-test likelihood of disease, the use of CT angiography will most likely not result in a 'negative' scan that would help avoid invasive angiography. Therefore, the use of CT angiography should be restricted to patients with an intermediate pre-test likelihood of CAD.

Several studies have evaluated the accuracy of CT angiography in specific clinical scenarios. Meijboom *et al*.[67] studied the diagnostic performance of 64-slice MDCT in patients referred for valve surgery and reported a sensitivity of 100% with a specificity of 92% and positive and negative predictive values of 82 and 100%, respectively, to identify patients with at least one significant stenosis. Other clinical scenarios included patients with dilated cardiomyopathy (sensitivity 99%, specificity 96%, positive and negative predictive values 81 and 99%.)[68] and patients with left bundle branch block (sensitivity 97%, specificity 95%, positive and negative predictive values 93 and 97%).[12] Another clinically relevant group of patients who often have a rather low likelihood of CAD but who must undergo diagnostic stratification are those presenting with acute chest pain. Hoffmann *et al*.[69] conducted a blinded, prospective study in patients presenting with acute chest pain to the emergency department to rule out an acute coronary syndrome in the absence of ischaemic ECG changes and negative initial biomarkers. Among 103 consecutive patients studied by 64-slice CT, 14 patients were diagnosed clinically to have an acute coronary syndrome. Both the absence of significant coronary artery stenosis (73 of 103 patients) and non-stenotic coronary atherosclerotic plaque (41 of 103 patients) accurately predicted the absence of an acute coronary syndrome (negative predictive value 100%). The positive predictive value was rather low, indicating false-positive results in a considerable number of scans (47% for the detection of significant stenoses, 14/30 positive scans), and only a small percentage of patients with acute chest pain were actually included in the study (103 of 305 initially screened patients). Goldstein *et al*.[26] randomized 197 patients with low-risk acute chest pain to an immediate 64-slice CT scan or 'standard of care' evaluation. CT was found to be safe, with no missed diagnosis of an acute coronary syndrome, faster (3.4 vs. 15 h until establishing the definitive diagnosis), and had lower cost ($1586 vs. 1872) compared with 'standard of care'. However, CT imaging did not completely eliminate the need for additional testing. In fact, stress testing was performed in 24 of 99 patients who underwent cardiac CT.

In summary, the clinical application of coronary CT angiography to detect or rule out coronary artery stenoses seems most beneficial and, according to current data, can be recommended in patients with intermediate risk of CAD in whom the clinical presentation—stable or with acute symptoms—mandates the evaluation of possible underlying CAD. A similar conclusion was reached in an expert consensus document on 'appropriate' indications for cardiac CT and cardiac magnetic resonance imaging which was published in October 2006 (*Table 3*).[70] The use of coronary CT angiography should be restricted to patients in whom

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Table 3 Appropriate clinical indications for the use of computed tomography coronary angiography and cardiac computed tomography imaging according to an expert consensus document endorsed by several professional societies and published in 2006[70]

Detection of CAD with prior test results—evaluation of chest pain syndrome (use of CT angiogram)
- Uninterpretable or equivocal stress test (exercise, perfusion, or stress echo)
- Intermediate pre-test probability of CAD
   ECG uninterpretable or unable to exercise

Detection of CAD: symptomatic—acute chest pain (use of CT angiogram)
- Intermediate pre-test probability of CAD
   No ECG changes and serial enzymes negative

Detection of CAD: symptomatic—evaluation of intra-cardiac structures (use of CT angiogram)
- Evaluation of suspected coronary anomalies

Structure and function—morphology (use of CT angiogram)
- Assessment of complex congenital heart disease including anomalies of coronary circulation, great vessels, and cardiac chambers and valves
- Evaluation of coronary arteries in patients with new onset heart failure to assess aetiology

Structure and function—evaluation of intra- and extra-cardiac structures (use of cardiac CT)
- Evaluation of cardiac mass (suspected tumour or thrombus)
   Patients with technically limited images from echocardiogram, MRI, or TEE
- Evaluation of pericardial conditions (pericardial mass, constrictive pericarditis, or complications of cardiac surgery)

Patients with technically limited images from echocardiogram, MRI, or TEE
- Evaluation of pulmonary vein anatomy prior to invasive radiofrequency ablation for atrial fibrillation
- Non-invasive coronary vein mapping prior to placement of biventricular pacemaker
- Non-invasive coronary arterial mapping, including internal mammary artery prior to repeat cardiac surgical revascularization

Structure and function—evaluation of aortic and pulmonary disease (use of CT angiogram[a])
- Evaluation of suspected aortic dissection or thoracic aortic aneurysm
- Evaluation of suspected pulmonary embolism

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[a]Non-gated CT angiogram which has a sufficiently large field of view for these specific indications.

diagnostic image quality can be expected (e.g. absence of arrhythmias), and scans need to be expertly performed and interpreted.

Coronary stent imaging

Visualization of the lumen of coronary artery stents remains a challenge for MDCT due to metal artefacts caused by stent struts (*Figure 3*).[71,72] High rates of unevaluable stents have been reported in studies using 16-slice systems, ranging from 5−49%.[73,74] With the more recently available 64-slice systems, in combination with dedicated reconstruction algorithms, a larger percentage of

stents may be eligible for evaluation (*Table 4*).[23,75−79] Six studies (with 482 patients and 682 stents) that have compared 64-slice CT and dual-source CT with invasive angiography for the detection of in-stent stenosis are currently available. On average, 88% of stents were interpretable. Interpretable stents could be evaluated with fairly high diagnostic accuracy; weighted mean sensitivities and specificities were 91% (95% CI 85−96) and 94% (95% CI 91−95), respectively. While the negative predictive value was uniformly high [90−99%, mean 98% (95% CI 96−99)], positive predictive values were as low as 63% [in mean 76% (95% CI 68−83)]. For
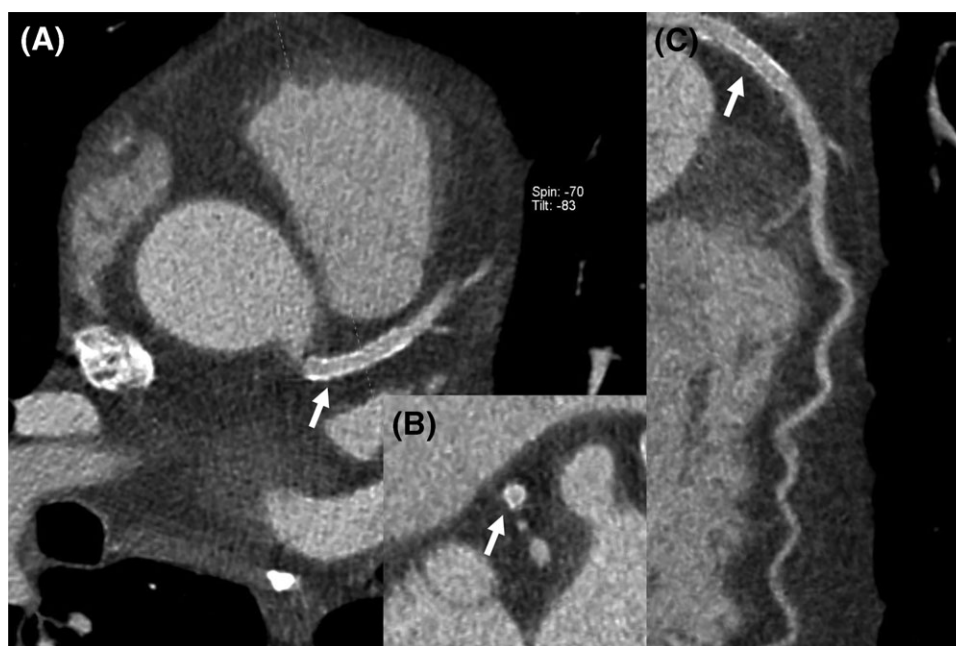

Figure 3 Assessment of coronary artery stents by multi-detector row computed tomography angiography. Example of a stent placed in the proximal part of the left anterior descending coronary artery. Image quality is good and the coronary artery lumen within the stent can be assessed. multi-detector row computed tomography shows absence of significant in-stent-stenosis. (*A*) Longitudinal view; (*B*) axial orientation; (*C*) curved multiplanar reconstruction.

Table 4 Diagnostic performance of 64-slice computed tomography and dual-source computed tomography for the detection of in-stent restenosis

Author	Number of patients/stents	Not evaluable (%)	Sensitivity (%)	Specificity (%)	PPV (%)	NPV (%)
Rixe et al.[79]	64/102	42 (43/192)	86 (6/7)	98 (51/52)	86 (6/7)	98 (51/52)
Rist et al.[78]	25/46	2 (1/46)	75 (6/8)	92 (34/37)	67 (6/9)	94 (34/36)
Oncel et al.[76]	30/39	0 (0/39)	89 (17/19)	95 (19/20)	94 (17/18)	90 (19/21)
Ehara et al.[23]	81/125	12 (15/125)	91 (20/22)	93 (82/88)	77 (20/26)	98 (82/84)
Cademartiri et al.[75]	182/192	7 (14/192)	95 (19/20)	93 (147/158)	63 (19/30)	99 (147/148)
Pugliese et al.[77]	100/178	5 (9/178)	94 (37/39)	92 (128/139)	77 (37/48)	98 (128/130)
Total	482/682	12 (82/682) (95% CI 9.7−15)	91 (105/115) (95% CI 85−96)	93 (461/494) (95% CI 91−95)	76 (105/138) (95% CI 68−83)	98 (461/471) (95% CI 96−99)

All values are expressed as per cent with absolute numbers in parentheses. Sensitivity and specificity were calculated only for evaluable stents.
95% CI, 95% confidence interval; NPV, negative predictive value; PPV, positive predictive value.

all scanner generations, the stent diameter has been identified as a major predictor of stent evaluability, with particularly low rates of evaluable stents for diameters ≤3.0 mm.[79] Patient weight, which determines image noise, and heart rate may also influence stent assessability.

Clinical implications and recommendations
Although in single, carefully selected cases (e.g. large diameter stents in a proximal vessel segment, low and stable heart rate, and absence of excessive image noise) coronary CT angiography may be a possibility to rule out in-stent restenosis, routine application of CT to assess patients with coronary stents can currently not be recommended. Visualization of the stent lumen is often affected by artefacts, and especially the positive predictive value is low.

Coronary artery bypass grafts
Coronary artery bypass grafts (CABGs) move less rapidly and particularly venous grafts have relatively large diameters compared with native coronary arteries (*Figure 4*). Occluded grafts and stenoses in the body of bypass conduits can therefore be detected with very high diagnostic accuracy (*Table 5*), although surgical metal clips may lead to artefacts that impair accurate visualization in some cases. Clinically, it is important to consider that, in most cases, it will not be sufficient to assess only the grafts themselves, but rather the distal run off, as well as the non-grafted coronary arteries must be included in the evaluation. However, accurate assessment of the native coronary arteries by cardiac CT in patients after CABG is often challenging and image quality impaired because of advanced CAD and pronounced coronary calcifications. Consequently, the studies that have investigated the accuracy of CT angiography to evaluate the native arteries in patients with bypass grafts have reported low accuracies. Although sensitivity for the detection of stenoses in the native vessels ranged from 79–100% [mean value 95% (95% CI 93–97)], specificity was uniformly lower [59–89%, mean value 75% (95% CI 72–78), negative

Figure 4 Coronary artery bypass graft imaging with multidetector row computed tomography. Cardiac computed tomography evaluation of the heart in an 82-year-old man 9 years after coronary artery bypass surgery. The curved multiplanar reconstruction (left panel) of the venous graft to the first obtuse marginal branch demonstrates a significant lesion in the proximal part (arrow), which is confirmed by invasive angiography (right panel).

predictive value 97% (95% CI 95–98)], and consequently, the positive predictive value was as low as 67% (95% CI 64–71)] (*Table 5*).[30,80–84] This severely limits the clinical utility of CT imaging in patients after bypass surgery.[30]

Clinical implications and recommendations
Although the clinical application of CT angiography may be useful in very selected patients in whom only bypass graft assessment is necessary (e.g. failed visualization of a graft in invasive angiography), the inability to reliably visualize the native coronary arteries in patients post-CABG poses severe restrictions to the general use of CT angiography in post-bypass patients.

Coronary artery anomalies
Although coronary anomalies are rare conditions, possible consequences include myocardial infarction and sudden death.[85] In young athletes, coronary artery anomalies are the second most common cause of sudden death due to structural heart disease.[86] The identification of the origin and course of aberrant coronary arteries by invasive angiography can be difficult.[87] Because of the three-dimensional nature of the data set, MDCT is very well suited to detect and define the anatomic course of coronary artery anomalies and their relationship to other cardiac and non-cardiac structures (*Figure 5*). Numerous case reports and several research papers have demonstrated that the CT analysis of coronary anatomy in these patients is straightforward and very reliable with an accuracy close to 100%.[88–91]

Clinical implications and recommendations
The robust visualization and classification of anomalous coronary arteries make CT angiography a first-choice imaging modality for the investigation of known or suspected coronary artery anomalies. Radiation dose must be considered often in the young patients, and measures to keep dose as low as possible must be employed.

Coronary plaque imaging

Calcium scoring
Coronary calcium is a surrogate marker for the presence and amount of coronary atherosclerotic plaque.[92,93] Both EBCT and MDCT permit accurate detection and quantification of coronary artery calcium.[93,94] The radiation dose for a calcium scan is in the range of 1–2 mSv.[95,96] The so-called 'Agatston Score', which takes into account the area and the CT density of calcified lesions, is most frequently used to quantify the amount of coronary calcium in CT, and large population reference databases are available. With the exception of patients with renal failure, calcifications occur exclusively in the context of atherosclerotic lesions.[92,93,97] The amount of coronary calcium correlates moderately closely to the overall atherosclerotic plaque burden.[98] On the other hand, not every atherosclerotic coronary plaque is calcified, and calcification is a sign of neither stability nor instability of an individual plaque.[99] Clinically, coronary calcium is detectable in the vast majority of patients with acute coronary syndromes, and the

Table 5 Diagnostic accuracy of 16- and 64-slice computed tomography multi-detector row computed tomography for the evaluation of patients after coronary artery bypass surgery
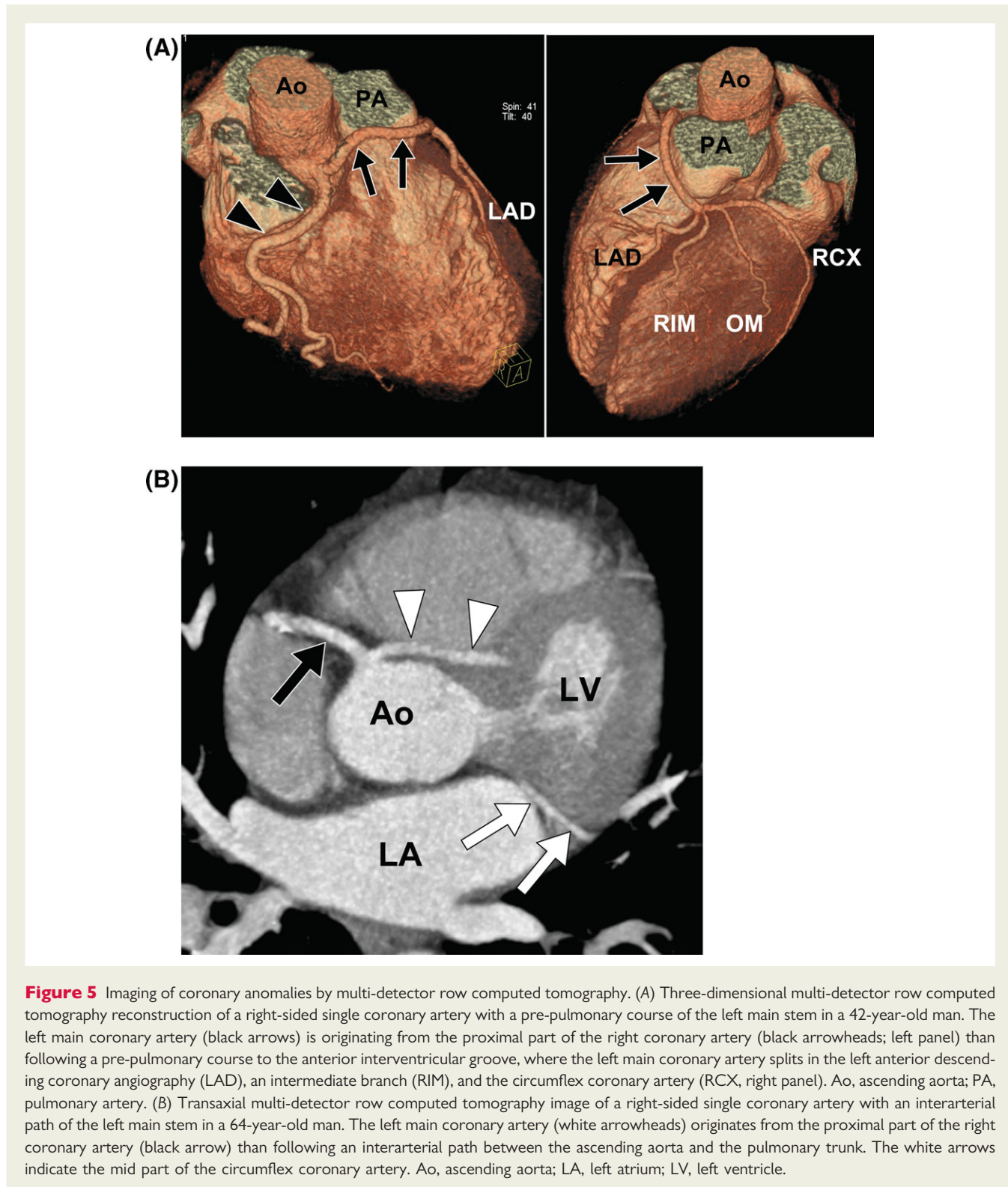
Author	Number of patients/grafts	Evaluation of	Not evaluable	Sensitivity (%)	Specificity (%)	PPV (%)	NPV (%)
Nieman et al.[82]	24/60[a]	Graft occlusion	0 (0/60)	O 1: 100 (17/17)	100 (42/42)	94 (17/18)	100 (42/42)
			5 (3/60)	O 2: 100 (17/17)	98 (39/40)	94 (17/18)	100 (39/39)
		Graft stenosis	10 (4/42)	O 1: 60 (3/5)	88 (29/33)	43 (3/7)	94 (29/31)
			5 (2/39)	O 2: 83 (5/6)	90 (28/31)	63 (5/8)	97 (28/29)
		Native arteries	34 (65/211)	O 1: 90 (71/79)	75 (50/67)	81 71/88)	86 (50/58)
			31 (61/211)	O 2: 79 (54/68)	72 (52/72)	73 (54/74)	79 (52/66)
Stauder et al.[84]	20/50	Graft occlusion	0 (0/50)	100 (17/17)	100 (229/229)	100 (17/17)	100 (229/229)
		Graft stenosis	12 (31/240)	99 (92/94)	94 (128/130)	92 (92/94)	99 (128/130)
		Native arteries	31 (81/260)	92 (105/114)	77 (50/65)	88 (105/120)	85 (50/59)
Burgstahler et al.[80]	13/43	Graft occlusion	0 (0/43)	100 (16/16)	100 (27/27)	100 (16/16)	100 (27/27)
		Graft stenosis	5 (2/43)	100 (1/1)	93 (25/27)	33 (1/3)	100 (25/25)
		Native arteries	32 (54/169)	83 (90/108)	59 (36/61)	78 (90/115)	67 (36/54)
Salm et al.[83]	25/67	Graft occlusion	0 (0/67)	100 (25/25)	100 (57/57)	100 (25/25)	100 (57/57)
		Graft Stenosis	NA	100 (3/3)	94 (51/54)	50 (3/6)	100 (51/51)
		Native arteries[b]	8 (17/225)	100 (11/11)	89 (16/18)	85(11/13)	100 (16/16)
Malagutti et al.[81]	52/109	Graft stenosis[c]	0 (0/109)	100 (49/49)	98 (59/60)	98 (49/50)	100 (59/59)
		Native arteries	NA	97 (62/64)	86 (50/74)	66 (62/94)	99 (192/194)
Ropers et al.[30]	50/138	Graft occlusion	0 (0/138)	100 (38/38)	100 (100/100)	100 (38/38)	100 (100/100)
		Graft stenosis	0 (0/138)	100 (31/31)	94 (17/19)	92 (31/33)	100 (17/17)
		Native arteries	9 (55/621)	86 (87/101)	76 (354/456)	44 (87/189)	96 (354/368)
Total		Graft occlusion	0.7 (3/418) (95% CI 0.15−2.1)	100 (130/130) (95% CI 97−100)	100 (494/495) (95% CI 99−100)	99 (130/131) (95% CI 96−100)	100 (494/494) (95% CI 99−100)
		Graft stenosis	6.4 (39/611) (95% CI 4.6−8.6)	97 (184/1889) (95% CI 94−99)	95 (337/354) (95% CI 92−97)	92 (184/201) (95% CI 87−95)	99 (337/342) (95% CI 97−100)
		Native arteries	19.6 (333/1697) (95% CI 18−22)	95 (524/545) (95% CI 93−97)	75 (608/813) (95% CI 72−78)	67 (424/629) (95% CI 64−71)	97 (608/629) (95% CI 95−98)

All values are expressed as per cent with absolute numbers in parentheses. Sensitivities and specificities are calculated only for evaluable bypass grafts and native arteries.

95% CI, 95% confidence interval; NA, not applicable; NPV, negative predictive value; O 1/O 2, observer 1 and observer 2 where applicable; PPV, positive predictive value.

[a]Venous grafts only.

[b]Evaluation was restricted to non-grafted vessels only.

[c]Defined as significant graft stenosis and/or occlusion.

Figure 5 Imaging of coronary anomalies by multi-detector row computed tomography. (*A*) Three-dimensional multi-detector row computed tomography reconstruction of a right-sided single coronary artery with a pre-pulmonary course of the left main stem in a 42-year-old man. The left main coronary artery (black arrows) is originating from the proximal part of the right coronary artery (black arrowheads; left panel) than following a pre-pulmonary course to the anterior interventricular groove, where the left main coronary artery splits in the left anterior descending coronary angiography (LAD), an intermediate branch (RIM), and the circumflex coronary artery (RCX, right panel). Ao, ascending aorta; PA, pulmonary artery. (*B*) Transaxial multi-detector row computed tomography image of a right-sided single coronary artery with an interarterial path of the left main stem in a 64-year-old man. The left main coronary artery (white arrowheads) originates from the proximal part of the right coronary artery (black arrow) than following an interarterial path between the ascending aorta and the pulmonary trunk. The white arrows indicate the mid part of the circumflex coronary artery. Ao, ascending aorta; LA, left atrium; LV, left ventricle.

amount of calcium in these patients is substantially greater than in matched control subjects without CAD.[100–103]

In several trials, the absence of coronary calcium ruled out the presence of significant coronary artery stenoses with high predictive value.[97,98] However, even pronounced coronary calcification is not necessarily associated with haemodynamically relevant luminal narrowing. Therefore, even the detection of large amounts of calcium does not indicate the presence of significant stenoses and it should not prompt invasive coronary angiography in otherwise asymptomatic individuals.

Numerous prospective trials have demonstrated that the presence of coronary calcium in asymptomatic individuals is a prognostic parameter with strong predictive power for future hard cardiac events.[97,98,104–108] Still, patient management approaches based on calcium assessment have not been prospectively investigated. A beneficial contribution of coronary calcium assessment to risk stratification can most likely be expected in individuals who seem to be at intermediate risk for coronary events (1.0–2.0% annual risk) on the basis of traditional risk factor analysis. Unselected 'screening' or patient self-referral is not recommended,[97,98,109] and the value of calcium scoring in individuals with very low (<1.0% annual risk) or very high risk (>2.0% annual risk) is discussed controversially.[97,110]

Although the coronary calcium score has been found to be progressive over time, only very preliminary studies are available that have linked progression of coronary calcium to cardiac event rates.[111] Results concerning the influence of lipid-lowering therapy on the progression of coronary calcium have been inhomogeneous.[97,104,112–114] In addition, the variability of coronary calcification measurements is high. Therefore, there is no current indication for repeated coronary calcium score measurements.[97,98,109]

Clinical implications and recommendations

The use of coronary calcium measurements by CT seems most beneficial in patients who, based on prior assessment of standard risk factors, seem to be at intermediate risk for future CAD events and in whom more information is needed to make a decision on intensifying risk factor modification (e.g. initiation of lipid-lowering therapy). Patients at high risk do not need further stratification, and in patients at obviously low risk, the likelihood of finding coronary atherosclerosis is too low to warrant CT imaging. Usually, 'intermediate risk' patients in whom the use of coronary calcium is assumed to provide incremental information are those with a 10-year PROCAM or Framingham Risk between 10 and 20%.[97,98]

Non-calcified plaque

There is growing interest concerning the ability of contrast-enhanced CT coronary angiography to detect (and possibly to quantify and to further characterize) non-calcified coronary atherosclerotic plaque[115] (Figure 6). Data on the accuracy of CT angiography to detect non-calcified plaque are limited to a small number of studies that have compared CT angiography with intravascular ultrasound (IVUS). Sensitivities for the detection of coronary segments with plaque were found to be ∼80–90% (which, however, was mostly based on the detection of calcified plaque).[116–119] Correlation of plaque area ($r = 0.55$) and plaque volume ($r = 0.83$) between CT angiography and IVUS was found to be moderate, and interobserver variability is high.[118,120] It has been shown that the extent of remodelling of coronary atherosclerotic lesions can be assessed by CT.[121] Some data are available concerning plaque characterization by CT. On average, the CT attenuation within 'fibrous' plaques is higher than within 'lipid-rich' plaques (mean attenuation values of 91–116 vs. 47–71 HU),[117,118,122–128] but there is large variability of these

Figure 6 Imaging of coronary atherosclerotic plaque by multi-detector row computed tomography. The contrast-enhanced multi-detector row computed tomography data set shows a non-calcified plaque in the proximal right coronary artery with substantial positive remodelling and only a mild associated reduction of the coronary lumen.

measurements, which currently prevents accurate classification of non-calcified 'plaque types' by CT.[127]

Prognostic data that would support clinical applications of plaque imaging by contrast-enhanced CT are scarce.[129] As opposed to coronary calcium assessment, no prospective trials have investigated the predictive value of non-calcified plaque in large groups of individuals. Preliminary retrospective, small studies with 23–46 participants have used CT to investigate plaque characteristics in patients after acute coronary syndromes in comparison with patients with stable angina. They reported a higher fraction of non-calcified plaque and more positive remodelling in patients with acute coronary syndromes and in lesions responsible for cardiac events.[130–133] One study found a significantly higher prevalence of plaque, with a CT attenuation <30 HU in lesions associated with acute coronary syndromes when compared with stable lesions.[134] One analysis of 100 patients who were followed for 16 months after coronary CT angiography demonstrated a higher cardiovascular event rate in patients with non-obstructive plaque detected by MDCT compared with individuals without any plaque.[135] Although these initial observations suggest that there may be a potential value of plaque imaging by CT coronary angiography for risk prediction, one must be aware that reliable visualization of coronary plaque requires the highest possible image quality which goes along with substantial expenses in radiation and contrast agent exposure. The use of CT angiography for risk stratification will therefore only be clinically indicated after a substantial advantage over other methods for risk prediction has been clearly demonstrated.

Clinical implications and recommendations
The fact that there is currently a lack of prospective clinical data that would support the use of contrast-enhanced CT angiography for the assessment of non-stenotic plaque does not allow clinical applications in asymptomatic individuals for the purpose of risk stratification. However, the tremendous potential of CT angiography for visualization and characterization of coronary plaques must be recognized and further research is strongly supported.

Non-coronary imaging

Left and right ventricular function

On commercially available workstations, functional parameters such as left and right ventricular end-diastolic and end-systolic volumes, stroke volume, ejection fraction, and myocardial mass can be calculated from cardiac CT angiography data sets (*Figure 7*). Various studies have shown that for these left ventricular functional parameters, MDCT correlated well with magnetic resonance imaging, echocardiography, or gated SPECT.[136–140] Some
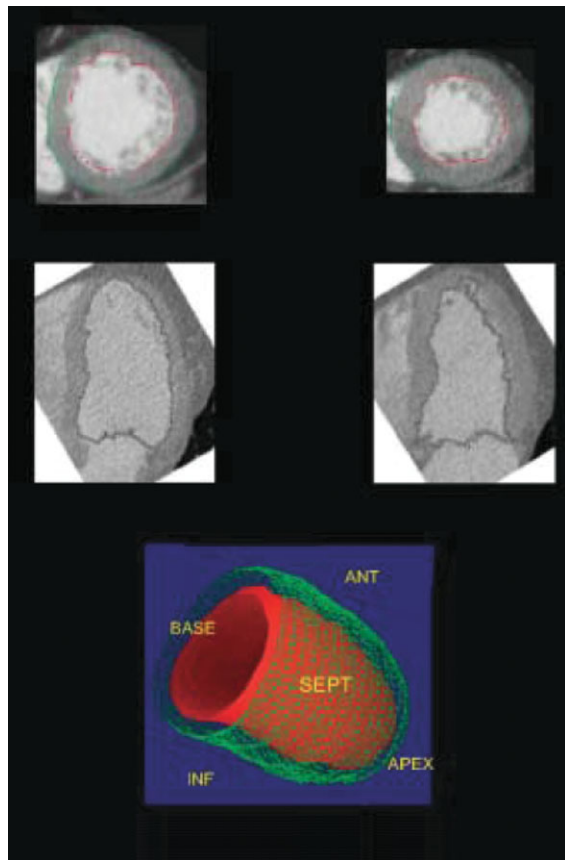
Figure 7 Assessment of left ventricular function and volumes by multi-detector row computed tomography. By tracing endocardial contours of standardized reformats in end-systolic and end-diastolic short- and long-axis views, left ventricular volumes and left ventricular ejection fraction can be derived from multi-detector row computed tomography data sets.

studies found a systematic over- or underestimation of left ventricular volumes determined by CT compared with the reference method. Most likely, these were due to inaccuracies in defining end-systolic or end-diastolic time instants. The magnitude of these differences was uniformly too small to be of clinical relevance.

Assessment of right ventricular function and volumes using MDCT has also been validated and found to be accurate in comparative studies with echocardiography,[141] and equilibrium radionuclide ventriculography,[142] in patients with various abnormalities including pulmonary embolism,[143] congenital heart disease,[144] and atrial septal defect.[145]

Clinical implications and recommendations
Although CT imaging allows accurate assessment of left and right ventricular function, CT examinations will in most cases not be performed specifically for that purpose. Other diagnostic tests without radiation exposure or the need for contrast injection (i.e. echocardiography) are the methods of choice. However, it should be noted that ventricular function is adjunct information that can be obtained from standard coronary CT angiography investigations without altering the image acquisition protocol, and the ability of CT to provide accurate right ventricular assessment might be useful in several clinical conditions including congenital heart disease, carcinoid heart disease, or prior to lung transplantation.

Myocardial viability and perfusion

Several pre-clinical and clinical studies have documented that MDCT allows assessment of myocardial viability by studying 'late enhancement' in a similar fashion as magnetic resonance imaging.[146–152] In the setting of acute, subacute, and chronic myocardial infarction, myocardial perfusion defects can be observed during the early phase of the contrast bolus ('early defect'). Subsequently, 5–15 min following contrast infusion, late hyperenhancement of infarcts becomes apparent (*Figure 8*). Lardo
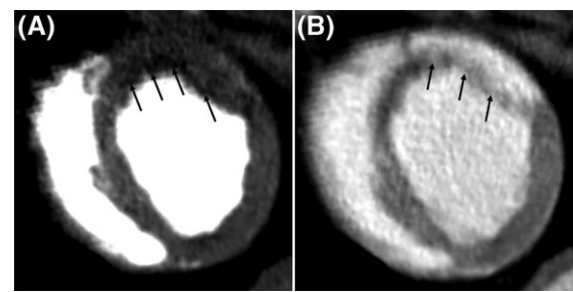

Figure 8 Assessment of perfusion and viability by multidetector row computed tomography. First-pass and delayed enhanced multi-detector row computed tomography myocardial imaging in a porcine model of subacute myocardial infarction. (*A*) demonstrates an 'early defect' in the anterior wall (arrows) during first-pass of the contrast bolus; (*B*) demonstrates a hyperenhanced, 'late defect' in the anterior myocardial wall (arrows) imaged 10 min following contrast infusion.

et al.[151] demonstrated excellent agreement of infarct size in the setting of acute infarction and chronic myocardial scar in pre-clinical animal models of infarction compared with gross patho-logy.[147] Similar results were demonstrated by Gerber et al.[149] in 16 and 21 patients with acute and chronic infarction, respectively. Mahnken et al.[152] studied 28 patients in the setting of reperfused infarction and demonstrated that compared with magnetic reson-ance imaging, early defects tend to underestimate infarct size in MDCT, whereas late enhancement shows excellent agreement in infarct size and location. Although these results appear promising, magnetic resonance remains the non-invasive gold standard to assess the size of myocardial scars.

Furthermore, there is pre-clinical and preliminary clinical evi-dence that contrast-enhanced MDCT can provide assessment of myocardial perfusion. As a complement to the morphological information of CT coronary angiography, the assessment of myo-cardial perfusion might be of clinical utility. George et al.[153] demon-strated in an animal model of coronary stenosis that MDCT angiography protocols, when performed during adenosine infusion, can provide semi-quantitative measures of myocardial perfusion.

Preliminary clinical evidence suggests that this same method, when applied to patients at high risk for CAD, may be capable of detecting early perfusion defects in myocardial territories sup-plied by vessels with obstructive atherosclerosis. The high spatial resolution of MDCT also allows for the assessment of the suben-docardial distribution of myocardial ischaemia.

Clinical implications and recommendations
Clinical data are currently too limited to allow clinical recommen-dations on the use of CT for the assessment of perfusion and viability.

Valvular disease
The assessment of aortic valve stenosis using MDCT is feasible with good diagnostic accuracy[154–158] (Figure 9). Rather than relying on gradients, MDCT allows direct planimetry of the aortic valve area. Feuchtner et al.[157] compared 16-slice MDCT with transthoracic echocardiography in 30 patients with aortic valve stenosis. The sensitivity of MDCT for the identification of patients with aortic stenosis was 100%, specificity was 93.7%,
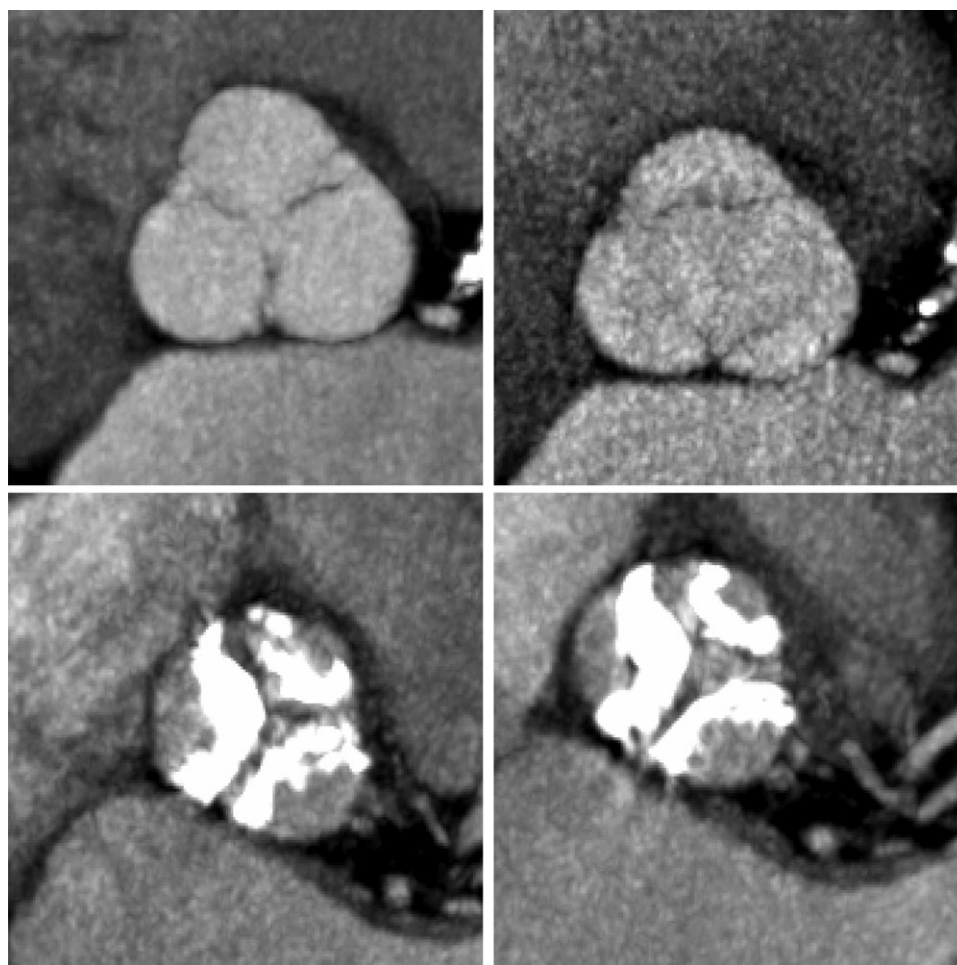

Figure 9 Assessment of valve disease by multi-detector row computed tomography. Aortic valve morphology assessed by computed tomo-graphy. Upper row: normal aortic valve (left: systolic phase of the heart cycle; right: diastolic phase); lower row: severely calcified aortic valve with aortic stenosis (left: systolic phase of the heart cycle; right: diastolic phase).

positive and negative predictive values were 97 and 100%. Planimetry of the aortic valve area by MDCT revealed a good correlation with orifice areas determined from transthoracic echocardiography through the continuity equation ($r = 0.89$; $P < 0.001$). Similarly, in 20 patients with aortic valve stenosis, Alkadhi et al.[154] reported an excellent correlation between the planimetrically assessed aortic valve areas in CT and transoesophageal echocardiography.

It is important to note that the use of ECG-triggered tube current modulation, which is usually applied in coronary CT angiography to limit overall radiation exposure to the patient, may interfere with reliable assessment of the aortic valve. Tube current modulation reduces the tube current in systole and may thus prohibit high-resolution imaging of the open aortic valve.

The accuracy to detect and quantify aortic valve regurgitation in comparison with transthoracic echocardiography has also been investigated by Feuchtner et al.[156] When a visible valvular leakage area was considered to be a diagnostic criterion for aortic regurgitation, the overall sensitivity of 16-slice MDCT for the identification of patients with aortic regurgitation was 81%, specificity 91%, positive predictive value 95%, and negative predictive value 70%. However, severe calcifications, which are more common in degenerative valvular disease, limited the diagnostic accuracy. In another study including 64 patients, planimetry of the diastolic regurgitant orifice area using 64-slice MDCT was compared with transthoracic echocardiography.[159] In 34 age-matched controls, no regurgitant orifice was found, whereas in all 30 patients, regurgitation was correctly diagnosed. These findings suggest that MDCT permits reliable assessment of aortic valve stenosis and regurgitation.

Willmann et al.[160] published data from patients with mitral valve disease in whom MDCT was performed. The authors found MDCT helpful for the detection of valvular abnormalities such as thickening of the mitral valve leaflets, presence of mitral annulus calcification, and calcification of the valvular leaflets. Agreement with echocardiography was achieved in 95–100% of cases. Alkadhi et al.[161] demonstrated that 16-slice MDCT allowed visualization of a regurgitant orifice in all 19 patients with mitral regurgitation. The mean regurgitant orifice area on MDCT was significantly related to the regurgitation severity ($r = 0.81$, $P < 0.001$) on transoesophageal echocardiography. Thus, MDCT seems to have the potential to visualize coaptation defects of the mitral leaflets.

Clinical implications and recommendations
CT imaging may develop into an alternative imaging tool in patients who require exact assessment of the opening or regurgitant orifice of the aortic or mitral valve and in whom other more commonly used methods, such as echocardiography and magnetic resonance imaging, fail to provide all relevant information. Currently, available clinical data are too limited to allow identification of specific patient subsets in which CT imaging would be the first-choice diagnostic test.

Venous anatomy
Anatomy of the coronary venous system can be accurately assessed with MDCT.[162,163] Recently, Van de Veire et al.[164]

demonstrated that the variability in venous anatomy may be related to previous infarction with formation of scar tissue. In 34 patients with a history of infarction, the left marginal vein was less frequently observed compared with control patients and patients with CAD (27 vs. 71 and 61%, respectively, $P < 0.001$). The absence of a left marginal vein in these patients may hamper the positioning of a left ventricular lead for cardiac resynchronization therapy if necessary. In this respect, MDCT may be a valuable tool for the non-invasive assessment of coronary venous anatomy before the implantation of a left ventricular lead or other interventions that make use of the cardiac veins.

Clinical implications and recommendations
Even though there is currently rather limited data, exact anatomy of the coronary veins cannot be obtained with imaging methods other than cardiac MDCT. If such information is desired, contrast-enhanced MDCT imaging will be a test of choice.

Left atrial and pulmonary vein anatomy
CT imaging allows accurate imaging of the anatomy of both atrial and pulmonary venous return, and in this context, the role of MDCT in performing electrophysiological procedures such as catheter ablation has rapidly expanded over the past few years.[165–167] Radiofrequency catheter ablation procedures are performed in an increasing number of patients with drug refractory atrial fibrillation. MDCT can provide a detailed 'roadmap' for these ablation procedures by visualizing the highly variable pulmonary vein anatomy with the use of volume-rendered three-dimensional reconstructions and cross-sectional images (*Figure 10*). Variations in pulmonary vein anatomy include a single insertion or 'common ostium' of the pulmonary veins, and an additional pulmonary vein. In 201 patients undergoing MDCT scanning, Marom et al.[167] noted a left-sided 'common ostium' in 14% of the patients and an additional right-sided pulmonary vein in 28% of the patients. By delineating surrounding structures such as the aorta, coronary arteries, and the oesophagus, MDCT is of great value to avoid complications during the ablation procedure.

Recently it has become feasible to integrate the anatomical information derived from MDCT with the electro-anatomical information from cardiac mapping systems to plan radiofrequency ablation of complex cardiac arrhythmias.[168,169] These image integration systems allow the use of 'real' anatomy derived from MDCT during the actual ablation procedure (*Figure 11*). By visualizing the catheter position in relation to the endocardial border, the pulmonary veins, and surrounding structures, performing catheter ablation procedures may be facilitated. Initial data indicate that the use of these image integration systems may enhance safety and improve the outcome of ablation procedures for atrial fibrillation.[170] In addition, MDCT is important in the follow-up of patients after catheter ablation procedures. The use of MDCT in the identification of pulmonary vein stenosis after catheter ablation has been described extensively,[171–173] and MDCT is an inherent part in the care of these patients.

Clinical implications and recommendations
There is growing evidence that MDCT imaging is useful in anatomical imaging of the heart, including pulmonary veins and the
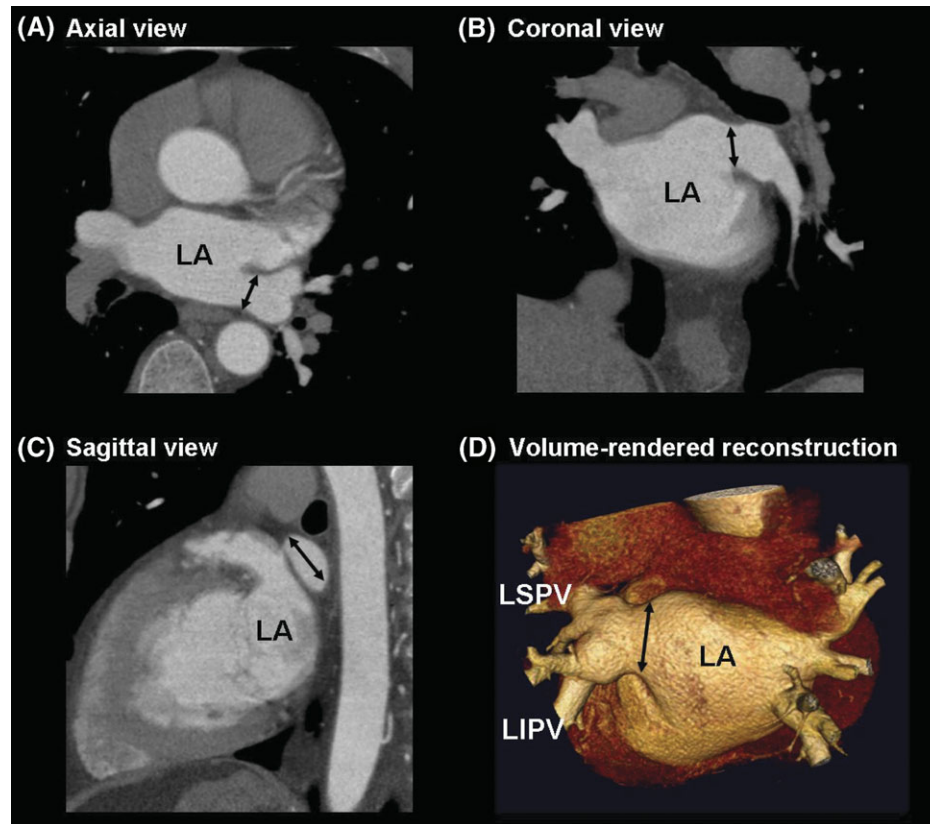
Figure 10 Imaging of the pulmonary veins by multi-detector row computed tomography. Anatomical variation of the pulmonary veins: a single insertion or 'common ostium' of the left-sided pulmonary veins is present. The veins come together before they drain in the left atrium (indicated by the black arrows). This is clearly depicted in the different orthogonal views (A, B, and C) and the volume-rendered reconstruction (D). LA, left atrium; LIPV, left inferior pulmonary vein; LSPV, left superior pulmonary vein.

coronary venous system, and the adjacent organs, e.g. prior to invasive electrophysiology procedures or in the follow-up after pulmonary vein ablation.

Congenital heart disease

Patients with congenital cardiovascular disease are frequently examined invasively and non-invasively to assess coronary anatomy and morphological as well as functional parameters. Because of the high spatial and temporal resolution, rapid image acquisition, and advanced post-processing tools, MDCT has become an important non-invasive diagnostic examination both in children and in adults with congenital heart disease.[174,175]

MDCT is a valuable tool in the pre-operative evaluation of cardiac anomalies (such as tetralogy of Fallot) and the follow-up of baffles and shunts. In addition, patients with untreated patent ductus arteriosus or coarctation of the aorta and patients with anomalous pulmonary venous return can be evaluated accurately with MDCT.[176] Furthermore, MDCT can depict coronary artery anatomy, which is often anomalous in patients with congenital heart disease. Cook and Raman[177] evaluated the MDCT data sets of 85 patients with congenital cardiovascular disease. The relationship of the great vessels, number and location of the coronary ostia, and proximal course of the coronaries could be

identified in all cases, and coronary anomalies were detected in 16 of the 85 patients.

Clinical implications and recommendations

Although MDCT provides detailed anatomic information, which is of major importance in the care of patients with congenital heart disease, it has to be taken into account that exposure to radiation during follow-up of these patients mainly stems from CT scans and angiography.[178] In particular, when serial evaluation over time is needed, non-ionizing imaging procedures (such as magnetic resonance imaging and echocardiography) should be considered. On the other hand, MDCT scanning is not hampered by the presence of pacemakers and metal artefacts and therefore may be indicated in patients with implanted devices if echocardiography does not provide all clinically necessary information. The utility of CT imaging in patients with congenital heart disease may well extend beyond the heart itself, to include structures such as the pulmonary vessels which are often affected in these patients and may be difficult to evaluate by echocardiography.

Incidental non-cardiac findings

When performing a cardiac CT scan, the anatomic status of the adjacent thoracic organs may also be evaluated, requiring an
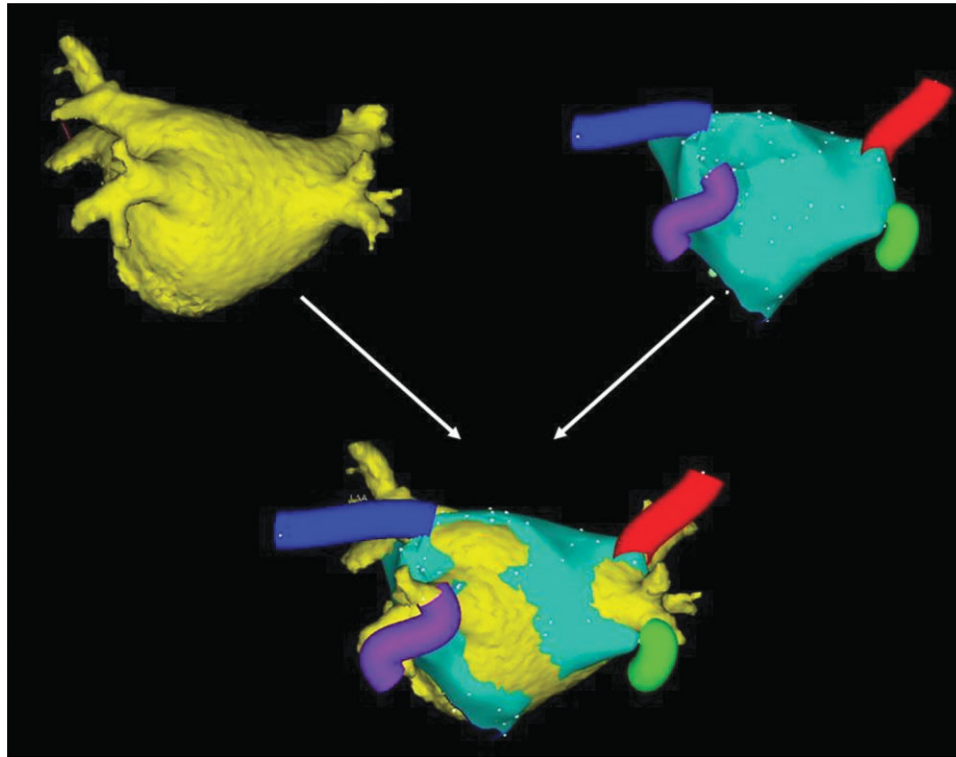
Figure 11 Fusion imaging in electrophysiology using multi-detector row computed tomography and electro-anatomical mapping. Integration of multi-detector row computed tomography and electro-anatomic map for catheter ablation of atrial fibrillation. With the use of image integration systems, the anatomy of the left atrium and pulmonary veins derived from the multi-detector row computed tomography (upper left panel) can be fused with the electroanatomic map (upper right panel). The 'real' anatomy of the left atrium and pulmonary veins can then be used to guide the catheter ablation procedure (lower panel).

image reconstruction with an extended field of view.[179] Several studies have reported a high prevalence of non-cardiac abnormalities in cardiac CT investigations. Hunold *et al*.[180] reported an incidence of pathological non-coronary findings of 53% (953 of 1812) consecutive EBCT scans used for calcium scoring. The vast majority of these findings however were without clinical relevance. Comparable results were published using contrast-enhanced 16-slice CT by Gil *et al*.[181] Of 258 asymptomatic patients, 145 (56.2%) were found to have a significant non-cardiac finding, including pulmonary abnormalities (emphysema, bullae, interstitial lung disease, masses, or nodules), pericardial abnormalities, liver disease, adrenal masses, and bone abnormalities.

Clinical implications and recommendations
Incidental non-cardiac findings are frequent on cardiac CT scans. Dedicated reconstructions are necessary to visualize all structures that were included in the scan range. Although the findings may be of clinical significance in some cases, weighing the risks and benefits associated with 'screening' for malignant pulmonary disease is difficult and there is currently no evidence that extending analysis of cardiac CT data sets beyond the heart will be useful to improve the outcomes of cardiac patients.[182]

Performing cardiac computed tomography in clinical practice

Training
Cardiac CT imaging requires competence on many levels. Data acquisition needs to be carefully performed, including necessary pre-medication, and appropriate measures are mandatory to keep radiation exposure within a reasonable range. Image reconstruction and post-processing require knowledge in CT physics, radiology, and cardiac physiology. Finally, competent image interpretation must be based on knowledge and experience in CT angiography, as well as detailed knowledge of cardiac anatomy, normal and variant patterns of the coronary circulation, and a thorough clinical background in CAD assessment. Obviously, conventional training in neither radiology nor cardiology will *per se* provide a sufficient background to perform and evaluate cardiac CT imaging. Although some speciality fellowship programmes in cardiac imaging and cardiac CT are available in select institutions, most cardiology and radiology training programmes do not incorporate mandatory exposure to cardiac CT at a volume that would

Table 6 Requirements for performing and interpreting cardiac computed tomography according to a competency statement issued by the American College of Cardiology and American HeartAssociation[183]

	Cumulative duration of training	Minimum number of mentored examinations performed	Minimum number of mentored examinations interpreted
Level 1	4 weeks	—	50
Level 2 (non-contrast)	4 weeks	50	150
Level 2 (contrast)	8 weeks	50	150
Level 3	6 months	100	300

suffice to provide competent diagnostic services in cardiac CT. In the USA, guidelines have been issued by professional societies that address minimum requirements in order to obtain competency in cardiac CT imaging.[183] In a statement on non-invasive cardiac imaging published by the American College of Radiology in 2005, the qualification of a radiologist who supervises and interprets cardiac CT examinations should include supervision and interpretation of 75 cardiac CT cases within 36 months, excluding cases performed exclusively for calcium scoring.[184]

In 2006, the American College of Cardiology and American Heart Association issued a joint statement concerning competency in cardiac CT imaging. Minimum requirements for competency in cardiac CT have been defined for three levels of proficiency (*Table 6*).[183] Briefly, for coronary CT angiography, Level 1 defines a basic knowledge of cardiac CT, which is sufficient for practice of general adult cardiology or general radiology, but not for independent interpretation of patient data sets. It requires 4 weeks of training as well as hands-on interpretation of 50 cases of CT coronary angiography. Level 2 training defines the minimum recommended experience in order to independently perform and interpret CT coronary angiography. Level 2 training requires a cumulative duration of 8 weeks, mentored performance of 50 contrast-enhanced and 50 non-contrast scans, and hands-on interpretation of 150 contrast-enhanced cardiac CT data sets. Level 3 training would qualify an individual to direct an independent cardiac CT programme. It requires 6 months of training, 100 cases performed, and 300 cases interpreted, plus 40 h of Continuing Medical Education. Required exposure to non-coronary cardiovascular pathology is not mentioned in these recommendations, even though such knowledge certainly would need to be acquired to be a competent reader of cardiac CT investigations.

No scientific data exist on the required amount of training to achieve a certain level of diagnostic confidence in cardiac CT, and the published recommendations are a consensus-based compromise between what is deemed necessary and possible. Although specific numbers are suggested, some issues remain open, such as the question as to what exactly constitutes a 'mentored examination'. Taped video documentation of a scanning procedure may be adequate for a certain percentage of these cases, but not for all of them, and many details are up to interpretation.

Eventually, similar guidelines will need to be developed for other countries, and ultimately, fellowship training in cardiology will need to incorporate sufficient exposure to cardiac CT, along with appropriate verification of knowledge.

Cost-effectiveness and reimbursement

Data on accuracy, prognostic implications, and cost-effectiveness must form the basis for establishing reimbursement for cardiac CT imaging. Currently, very little data that firmly establish prognostic implications of CT coronary angiography and little data on cost-effectiveness in relation to established diagnostic procedures are available. Initial studies in two of the most promising applications of cardiac CT, the use of CT angiography in patients with stable chest pain and the use of CT in patients who present to the emergency room with chest pain, indicate potential cost advantages for CT imaging over established, conventional diagnostic algorithms.

Dewey *et al*.[185] compared the cost of CT angiography, stress magnetic resonance imaging, and traditional diagnostic modalities, which encompassed exercise ECG, stress echocardiography, and conventional angiography. The authors could show that for a pre-test probability up to 50%; CT coronary angiography (with costs of €1469–4435) was most cost-effective. For pre-test likelihoods exceeding 60%, invasive angiography was most cost-effective. Goldstein *et al*.[26] analysed cost-effectiveness in their study of 197 patients admitted to the emergency room for acute chest pain but who were deemed at low risk for CAD. The authors demonstrated that incorporation of CT angiography into the workup was safe and highly accurate. Moreover, a diagnostic algorithm based on CT was more rapid (3.4 vs. 15.0 h, $P < 0.001$) and less costly (\$1856 vs. 1872, $P < 0.001$) than a standard diagnostic algorithm on the basis of repeat ECG and blood testing as well as stress perfusion imaging.

However, large studies on cost-effectiveness are obviously needed. Importantly, costs will vary significantly from country to country and depend on the local costs of equipment, maintenance, personnel, space, and many other factors in addition to the relative rates of reimbursement in various countries. Reimbursement of cardiac CT is currently inhomogeneous between countries and often even between health insurance carriers within a given country. In most countries, there is no specific reimbursement for cardiac CT procedures. When reimbursement is established, it should be taken into account that performing and evaluating cardiac CT scans, at least with current technology, require more dedicated effort than the majority of standard chest CT examinations (with the need for pre-medication, ECG gating, dedicated reconstructions at various cardiac phases), which should be reflected by the reimbursement structure.

Summary

The most recent MDCT scanner generations allow for robust morphological and functional imaging of the heart. Clinically, the main focus of cardiac CT is coronary artery imaging. The assessment of coronary anomalies by coronary CT angiography is straightforward and CT is indicated for that purpose. Under certain prerequisites, which include a low and regular heart rate, a carefully performed coronary CT angiography investigation allows for the accurate detection of coronary artery stenoses. Especially, the negative predictive value has uniformly been found to be high, indicating that the technique may be most suitable as a non-invasive tool to rule out the presence of obstructive coronary lesions. On the basis of clinical considerations and initial clinical trials, this may be of particular utility in situations that require to reliably rule out CAD even though the pre-test likelihood for disease is not high, such as in patients with atypical chest pain, patients with equivocal stress test results, patients with acute chest pain in the absence of ECG changes or enzyme elevations, or patients before non-coronary cardiac surgery. In these situations, the rationale for using CT is to achieve more rapid and definitive stratification and to avoid invasive coronary angiography if CT demonstrates the absence of stenoses. In patients with a high pre-test likelihood of disease, however, the use of CT angiography will most likely not result in a 'negative' scan that would help to avoid invasive angiography and is therefore not recommendable.

Several situations currently pose challenges for reliable CT imaging: these include patients with arrhythmias, patients with advanced CAD and pronounced coronary calcifications, and patients with coronary artery stents, which are often difficult to evaluate. Similarly, although CABGs can be assessed with very high diagnostic accuracy, detection of stenoses at the site of anastomosis and in the native coronary arteries of patients after CABG has reduced accuracy. Coronary CT angiography is not routinely recommendable in these situations.

Besides the detection of coronary stenoses, cardiac CT has the potential to visualize earlier stages of coronary atherosclerosis. Coronary calcium, a surrogate marker for the presence and amount of coronary atherosclerotic plaque, can be detected and quantified by non-contrast CT. Coronary calcium allows to stratify asymptomatic individuals concerning their future cardiovascular risk with a predictive power that is stronger than and independent of traditional cardiovascular risk factors. Coronary calcium measurements by CT may be useful in patients who, based on prior assessment of standard risk factors, seem to be at intermediate risk for future CAD events and may be appropriate in order to facilitate a decision concerning lipid-lowering therapy or other risk factor modification. Contrast-enhanced coronary CT angiography allows the detection and, to a certain degree, the characterization of non-calcified coronary atherosclerotic plaque. However, clinical data concerning the accuracy of plaque detection and characterization by contrast-enhanced CT, as well as its prognostic significance, are currently insufficient, so applications for risk stratification can currently not be recommended.

Besides the assessment of the coronary arteries, CT provides for accurate assessment of general cardiac morphology. This can be particularly useful in the context of electrophysiology when detailed anatomic information (e.g. the pulmonary veins and left atrium prior to ablation procedures or coronary veins in CRT for left ventricular lead placement) is needed. Similarly, CT imaging can be useful in patients with congenital heart disease or other structural cardiac disease, especially when echocardiography does not provide sufficient information and magnetic resonance imaging cannot be performed (e.g. in the presence of pacemakers/defibrillators). Although information on flow velocities and intracardiac pressures cannot be obtained by CT, assessment of right and left ventricular function is accurate. Also, the aortic and mitral valve can be depicted throughout the cardiac cycle and their orifice areas can be measured. Early data also indicate that perfusion and infarct imaging of the myocardium are possible. However, for many of these issues, CT imaging will not frequently be used as the first-line diagnostic modality because of the associated contrast agent and radiation exposure.

Although clinical application of cardiac CT is possible today in the situations outlined earlier, it can be expected that technology will continue to evolve rapidly. Spatial and temporal resolution will increase further, current indications as well as cost-effectiveness will be more firmly established by large clinical trials, and new applications will be developed. In addition, it will be necessary to establish adequate training programmes for cardiac CT, and to develop reimbursement structures which, tied to stringent guidelines on specific clinical situations for which cardiac CT is considered appropriate, will be necessary to allow more widespread use of CT in the diagnostic workup of patients with cardiac disease.

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