Comparison between the image quality of multisegment and halfscan reconstructions of non-invasive CT coronary angiography

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ABSTRACT. The purpose of this study was to compare the image quality of multisegment and halfscan reconstructions of multislice computed tomography (MSCT) coronary angiography. 126 patients with suspected coronary artery disease and uninfluenced heart rates were examined by 16-slice CT before they underwent invasive coronary angiography. Multisegment and halfscan reconstructions were performed in all patients, and subjective image quality, overall vessel length, vessel length free of motion artefacts and contrast-to-noise ratios (CNRs) were compared for both techniques. The diagnostic accuracy of both approaches was compared with the results of invasive coronary angiography. Overall image quality scores of multisegment reconstruction were superior to those of halfscan reconstruction (13.3 ± 2.1 vs 11.9 ± 2.9 ; $p < 0.001$). Multisegment reconstruction depicted significantly longer overall coronary vessel lengths ($p < 0.001$) and larger vessel proportions free of motion artefacts in three of the four main coronary arteries. CNRs in the left main, left anterior descending and left circumflex coronary arteries were significantly higher when multisegment reconstruction was used ($p < 0.001$). Overall accuracy was higher for multisegment reconstruction compared with halfscan reconstruction (87% vs 62%). In conclusion, multisegment reconstruction significantly improves image quality and diagnostic accuracy of MSCT coronary angiography compared with standard halfscan reconstruction, resulting in vessel lengths depicted free of motion comparable to those of CT performed in patients given β -blockers to lower heart rates.

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Non-invasive coronary angiography is an alternative approach to conventional coronary angiography in patients with suspected coronary artery disease (CAD) with high clinical [1–4] and economic [5] relevance. Recently, multislice computed tomography (MSCT) has developed into the most reliable non-invasive method for imaging of the whole coronary artery tree [6]. The susceptibility of MSCT to motion artefacts can only be overcome by systematic pre-scan β -blockade to lower heart rates to target values below 65 beats per minute (bpm). Recent studies have shown that β -blocker administration is necessary even on 64-slice scanners [4, 7–11]. Motion artefacts result from a relatively long acquisition window, which is determined by the gantry rotation time in standard halfscan reconstruction. In contrast, multisegment reconstruction [12] reduces the acquisition time by using up to four different segments from up to four consecutive heart beats [13]. In this way, an acquisition window as short as one-eighth of the gantry rotation time can be achieved [14]. In a small retrospective study of 34 patients with suspected CAD, multisegment reconstruction showed superior image quality and diagnostic accuracy compared with halfscan reconstruction. Based on these results, it was suggested that there is no

need for β -blocker administration when multisegment reconstruction is used [15]. However, a recently published subgroup analysis of patients with different heart rates showed that image quality and diagnostic performance of multisegment reconstruction varied with heart rate [16]. Therefore, the use of β -blockers was recommended in patients with heart rates above 75 bpm when using multisegment reconstruction.

In this study, we analysed prospectively the overall image quality and diagnostic accuracy of multisegment reconstruction compared with halfscan reconstruction in a large consecutive group of patients with uninfluenced heart rates to determine whether systematic β -blockade is needed.

Methods and materials

126 consecutive patients (95 men and 31 women; age range, 41–84 years, mean age, 63 ± 9 years) referred to our institution with suspected CAD were investigated by 16-slice CT before invasive coronary angiography. Patients with known CAD, unstable angina pectoris, irregular heart rates, known allergies to iodinated contrast agents, renal failure (serum creatinine level ≥ 1.5 mg dl⁻¹) or an inability to follow breath-hold commands were excluded. The study protocol was approved by the institutional ethics committee and the

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Federal Department of Radiation Protection; all patients gave written informed consent.

CT data acquisition

Patients were examined on a 16-slice CT scanner (Toshiba Medical Systems, Otawara, Japan). Data were acquired after inspiration with 400 ms gantry rotation time, 16×0.5 mm collimation, 0.35×0.35 mm² pixel size (10 line pairs per cm), 120 kV, 300 mA and 4 mm s⁻¹ table speed. Non-ionic iodinated contrast agent (iodixanol 320 (Visipaque; GE Healthcare Biosciences, Buckinghamshire, UK)) was injected intravenously at a flow rate of 3.5 ml s⁻¹. The manual bolus-tracking option of the scanner was used to visualise the influx of the contrast medium and to start image acquisition. Contrast administration was stopped when the helical scan reached the level of the left main coronary artery (LMA) in order to avoid streak artefacts arising from the right atrium and limiting the assessment of the right coronary artery (RCA). A simultaneous electrocardiogram (ECG) was recorded to allocate retrospectively the source images to the respective phases of the cardiac cycle (ECG gating). No β -blockers were given before the examination, and pre-oxygenation was used in patients who could not hold their breath for at least 30 s [17].

CT image reconstruction

Two reconstruction algorithms were employed: (i) adaptive multisegment image reconstruction [12], which uses up to four segments correlated with the raw data from up to four consecutive heartbeats, and (ii) standard halfscan reconstruction, which uses a single 180° gantry rotation. Multisegment reconstruction reduces acquisition time to a minimum of 50 ms; however, at different so-called "synchronisation time points", the image acquisition time is the same as that in halfscan reconstruction, where the time is fixed to 200 ms [18]. 10 axial image series were reconstructed at 10% intervals, with the centre of the reconstruction window being between 0% and 90% of the cardiac cycle, for both multisegment and halfscan reconstructions. Image series were transferred to a commercially available workstation (Vitrea 2, Version 3.3; Vital Images, Plymouth, MN).

Conventional coronary angiography

Conventional coronary angiography was performed after CT using standard techniques. All 15 coronary segments were evaluated for the presence of significant stenoses (diameter reductions $\geq 50\%$) by an experienced cardiologist using quantitative coronary angiography. Vessel segments with diameters ≥ 1.5 mm were included, as these segments may be a target of revascularisation.

CT analysis

The image reconstruction window with the fewest motion artefacts for each coronary artery was selected by

an experienced reader (a radiologist with 5 years of experience in CT coronary angiography) and used for further assessment of both reconstruction methods. Another reader (a radiology resident with 2 years of experience in CT coronary angiography), blinded to clinical data and the reconstruction algorithm used, created curved multiplanar reformations of the four main coronary arteries — LMA, left anterior descending coronary artery (LAD), left circumflex coronary artery (LCX) and RCA — using an automatic vessel detection tool [19]. The overall length of each main coronary vessel and the length free of motion artefacts were determined by the second reader by measuring the length of the centreline from the ostium to the most distal point at which the vessel lumen was still visible and to where the first motion artefact occurred, respectively [20, 21]. Image quality was assessed on the basis of axial, coronal and sagittal images on a five-point Likert scale, which ranged from 5 (very good) to 1 (poor, no evaluation possible), by comparing contour sharpness, the contrast between the coronary artery lumen and surrounding tissue, and the visibility of side branches. Overall image quality was calculated by adding these three scores. Significant stenoses were determined as diameter reductions $\geq 50\%$ in any of the 15 coronary artery segments. If a significant stenosis was detected, the patient was classified as positive for CAD. In cases with motion artefact in any segment but no significant stenosis in any other segment, the patient was classified as unassessable.

To determine contrast-to-noise ratios (CNRs), circular regions of interest (ROIs) ($3\text{--}4$ mm²) were placed by one experienced reader (D.S.) into the coronary lumen, 0.5 cm distal to the coronary ostium or the bifurcation of the LMA, and in the surrounding tissue. The mean Hounsfield units in these two ROIs were determined. Image noise was measured by placing a ROI (10 mm²) in the lumen of the aortic root at the level of the LMA and determining the standard deviation (SD) of the Hounsfield units measured in this ROI [21]. The CNR was calculated according to the following formula:

$$\frac{\text{Hounsfield unit}_{\text{lumen}} - \text{Hounsfield unit}_{\text{surrounding tissue}}}{\text{Image noise}_{\text{aortic root}}} \quad (1)$$

Statistical analysis

All data are expressed as means $\pm$ SD. The paired Student's *t*-test (parametric data) and Wilcoxon's test for paired samples (non-parametric data) with adjustment for multiple measurements were used to calculate the statistical significance of the differences between the two reconstruction methods in the parametrically defined vessel lengths and contrast measurements, and the non-parametric image quality scores. McNemar's test was used to compare the diagnostic accuracy, sensitivity and specificity, whereas the χ^2 test or Fisher's exact test was used to compare the negative and positive predictive values and non-diagnostic rate of either multisegment or halfscan reconstructions. Statistical analyses were performed using SPSS version 12.0 (SPSS Inc., Chicago, IL). A level of $p \leq 0.05$ was considered significant.

Results

Examinations were completed in all 126 patients without technical problems. In total, 502 coronary arteries were analysed; two vessels were not available, as one patient had no LCX and another had no LMA. The mean heart rate during the MSCT scan was 70 ± 10 bpm. The calculated width of the reconstruction window was 146 ± 36 ms for multisegment reconstructions. Halfscan reconstruction had a fixed reconstruction window of 200 ms.

Vessel lengths and motion artefacts

The mean depicted coronary artery length and the proportion depicted free of motion artefacts were both significantly longer using multisegment reconstruction compared with halfscan reconstruction in three of the four main coronary arteries: The mean vessel lengths depicted by multisegment *vs* halfscan reconstruction were 131 ± 32 mm *vs* 128 ± 32 mm in the LAD, 97 ± 34 mm *vs* 93 ± 33 mm in the LCX and 148 ± 41 mm *vs* 141 ± 44 mm in the RCA (all $p < 0.01$), and 11 ± 5 mm *vs* 11 ± 5 mm in the LMA ($p = 0.05$). The short and relatively large LMA was depicted adequately with both reconstruction algorithms, whereas halfscan reconstructions showed more motion artefacts in the distal and smaller parts of the coronary artery tree and side branches. The proportions of each vessel depicted free of motion artefacts were: (i) LAD, 96% using multisegment reconstruction *vs* 75% using halfscan reconstruction; (ii) LCX, 93% *vs* 62%; (iii) RCA, 82% *vs* 47% (all $p < 0.01$) and (iv) LMA, 99% *vs* 96% ($p = 0.05$). For a total of 138 vessels (27%), the vessel lengths depicted without motion artefacts were the same with both reconstruction algorithms: 320 vessels (64%) were depicted with a longer motion-free vessel length by multisegment reconstruction and 44 vessels (9%) by halfscan reconstruction. Figure 1 is a graphic representation of the mean lengths of the four main coronary vessels. These findings are underlined by the image quality scores. The quality scores assigned for vessel continuity, depiction of side branches and contrast were significantly higher using multisegment reconstruction than when using halfscan reconstruction. The overall image quality score was 13.3 ± 2.1 using multisegment reconstruction and 11.9 ± 2.9 using halfscan reconstruction ($p < 0.01$). Details of the image quality scores are listed in Table 1. Figures 2 and 3 show representative volume-rendered illustrations and curved multiplanar reformations of the heart and the coronary arteries in two different patients using multisegment and halfscan reconstructions.

Diagnostic accuracy

Diagnostic accuracy was much higher using multisegment reconstruction than with halfscan reconstruction. Compared with invasive coronary angiography, multisegment reconstruction achieved correct results in 108 out of 126 patients (accuracy, 86%), whereas halfscan reconstruction achieved a correct result in 78 out of the 126 patients (accuracy, 62%; $p < 0.01$). Multisegment reconstruction detected 62 of 67 patients with CAD (sensitivity, 92.5%), whereas halfscan reconstruction

Figure 1. Coronary vessel lengths (mean $\pm$ standard deviation; in mm) depicted with multisegment reconstruction (dark bars) and halfscan reconstruction (bright bars). The total vessel length and the artefact-free vessel length were both significantly longer with multisegment reconstruction than with halfscan reconstruction in three of the four main coronary arteries (* $p < 0.001$ using Student's paired *t*-test), but not in the LMA. LMA, left main coronary artery; LAD, left anterior descending coronary artery; LCX, left circumflex coronary artery; RCA, right coronary artery.

detected 60 of these 67 patients (sensitivity, 89.5%; $p < 0.01$). Specificity rates varied substantially; multisegment reconstruction identified 46 of 59 patients without CAD correctly (specificity, 78%), whereas halfscan reconstruction identified only 18 of these 59 patients owing to the higher amount of motion artefacts (specificity, 30.5%; $p < 0.01$). Patients were not assessable in 9 out of 126 cases using multisegment reconstruction (7%), whereas 43 of 126 patients were not assessable using halfscan reconstruction (34%). Positive and negative predictive values were 93% (62/67) and 92% (46/50), respectively, using multisegment reconstruction, compared with 92% (60/65) and 100% (18/18) using halfscan reconstruction (all non-significant p -values). The majority of CT data using halfscan reconstruction from patients without significant stenoses was impaired by motion artefacts, leading to the small number of 18 truly negative (identified) patients.

On a per artery basis, overall accuracy was 87% using multisegment reconstruction compared with 62% using halfscan reconstruction ($p < 0.01$). All other diagnostic parameters also differed substantially on the per artery basis: sensitivity, 83% *vs* 66% ($p < 0.01$); specificity, 89% *vs* 60% ($p < 0.01$); non-diagnostic rate, 6% *vs* 34% ($p < 0.01$); positive predictive value, 88% *vs* 85% (non-significant p -value); and negative predictive value, 96% *vs* 97% (non-significant p -value).

Contrast measurements

Calculated CNRs were significantly higher for multisegment reconstruction than for halfscan reconstruction for all coronary arteries except the RCA. CNRs and the attenuation levels of each coronary artery are summarised in Table 2. The main reason for the higher ratio

Table 1. Comparison of image quality scores between multisegment and halfscan reconstructions in the per-vessel analysis ($n=502$)

	Multisegment reconstruction	Halfscan reconstruction	p -Value ^a
Continuity	4.6 ± 0.9	3.9 ± 2.7	<0.001
Side branches	4.5 ± 0.91	4.1 ± 1.3	<0.001
Contrast	4.1 ± 0.8	3.9 ± 1.0	<0.001
Total	13.3 ± 2.1	11.9 ± 2.9	<0.001

Values are mean $\pm$ standard deviation

^aCompared using Wilcoxon's test for paired samples; image quality was assessed using a five-point Likert scale from 5 (very good) to 1 (poor, no evaluation possible)

was a significantly lower noise level measured in the aorta ($p=0.011$), whereas the CT attenuation levels of the coronary artery lumina differed only significantly in the LAD ($p=0.039$) and the LCX ($p=0.043$). The values of the surrounding tissue were not significantly different ($p=0.05$; Table 2).

Discussion

Non-invasive coronary artery imaging is technically ambitious because there is pronounced vessel motion

during the cardiac cycle. Recent technical advances have led to the development of scanners with a sufficiently high temporal and spatial resolution for coronary artery imaging but only in patients with low heart rates [1–4]. The majority of recent studies investigating standard halfscan reconstruction recommend the use of β -blockers in order to reduce motion artefacts even in patients examined on 64-slice scanners [11]. β -blocker administration makes the procedure more complicated and is sometimes contraindicated, *e.g.* in patients with moderate to severe bronchial asthma. We therefore investigated the image quality of MSCT coronary angiography in a large consecutive cohort of prospectively recruited patients without pre-scan β -blocker administration using both multisegment and standard halfscan reconstructions. In this patient population, multisegment reconstruction achieved a significantly better image quality compared with halfscan reconstruction owing to a reduction of motion artefacts. This is reflected in longer vessel segments depicted free of motion artefacts, a better depiction of coronary side branches and of the

Figure 2. Volume renderings of the heart of a 60-year-old man with a heart rate of 92 beats per minute from (a,b) multisegment and (c,d) halfscan reconstructions. Halfscan reconstruction is degraded by so-called “stair-step” artefacts (yellow arrows), resulting from an insufficient temporal resolution of 200 ms. In multisegment reconstruction, the reconstruction window is 93 ms in width. The significant stenosis in the first diagonal branch (white arrows) is clearly revealed with multisegment reconstruction (a), whereas it is missed with halfscan reconstruction (c). The right coronary artery of the same patient is depicted without artefacts using multisegment reconstruction (b), whereas halfscan reconstruction shows a right coronary artery severely degraded by motion artefacts (d).

Figure 3. Curved multiplanar reformation of the right coronary artery in a patient with typical angina pectoris and a heart rate of 64 beats per minute: (a) multisegment and (b) halfscan reconstruction. Halfscan reconstruction is degraded by motion artefacts (arrowheads), whereas multisegment reconstruction clearly depicts the entire coronary artery without motion artefacts.

Table 2. Results of contrast measurements for multisegment and halfscan reconstructions

	Multisegment reconstruction	Halfscan reconstruction	p-Value ^a
Noise ^b	17.9 ± 4.3	18.9 ± 5.3	0.011
LMA			
HU _{Vessel}	289 ± 57	284 ± 64	>0.05
HU _{Tissue}	-41 ± 38	-38 ± 34	>0.05
CNR	19.2 ± 5.3	18.1 ± 5.8	0.012
LAD			
HU _{Vessel}	274 ± 59	266 ± 59	<0.039
HU _{Tissue}	-48 ± 39	-46 ± 37	>0.05
CNR	18.8 ± 5.6	17.7 ± 6.4	0.013
LCX			
HU _{Vessel}	259 ± 57	249 ± 57	<0.042
HU _{Tissue}	-37 ± 35	-38 ± 34	>0.05
CNR	17.3 ± 5.3	16.3 ± 5.8	0.007
RCA			
HU _{Vessel}	268 ± 61	264 ± 65	>0.05
HU _{Tissue}	-39 ± 34	-39 ± 33	>0.05
CNR	17.9 ± 5.5	17.2 ± 6.4	>0.05

HU, Hounsfield units; CNR, contrast-to-noise ratio; LMA, left main coronary artery; LAD, left anterior descending coronary artery; LCX, left circumflex coronary artery; RCA, right coronary artery

^aCNR and noise were compared using Wilcoxon's test for paired samples

^bNoise was measured as the standard deviation in the aortic root, as described in [21]

distal parts of the coronary artery tree, and in higher contrast gradings.

Comparison with other studies

The mean length of each coronary artery visualised in our study was longer than previously reported for 4-slice MSCT scanners [21] and electron beam CT [21, 22] or magnetic resonance angiography [23–27]. The measured overall length of the coronary arteries was comparable to

the results of previously published studies using 16-slice [15, 20] and 64-slice scanners [28] (Table 3). One study performed on a 16-slice scanner measured shorter vessel lengths, which might have been because the investigators did not fully exploit the possible spatial resolution, as they used a reconstruction resulting in pixel sizes of $0.8 \times 0.8 \text{ mm}^2$ [26]. In the present study, multisegment reconstruction substantially improved the vessel lengths visualised without motion artefacts: on average, 90% of the coronary artery tree was visualised until the first motion artefact was encountered. With a 4-slice scanner,

Table 3. Comparison of image quality parameters reported in recent clinical studies of non-invasive coronary angiography^a

Modality	Current study	Ferencik et al [28]	Kefer et al [26]		Dewey et al [15]	Ferencik et al [20]	Achenbach et al [21]	
	16-slice CT	64-slice CT	16-slice CT	MRI	16-slice CT	12-slice CT	4-slice CT	EBT
Number of patients	126	42	52	52	42	30	30	30
Effective slice thickness (mm)	0.5	0.6	0.75		0.5	0.75	1.0	3.0
Heart rate (bpm)	70 ± 8 ^b	63 ± 10	66 ± 10	67 ± 13	73 ± 12 ^b	62 ± 13	77	76
Gantry rotation time (ms)	400	330	420		500	420	500	
Length of the image reconstruction window (ms)	146 ± 35	165	90–120	90	156 ± 42	210	188 ± 41	NS
CNR ^c	18.3 ± 5.5	14.6 ± 4.7	6.9 ± 2.8	8.3 ± 2.9	14 ± 6.6	9.9 ± 3.1	9.0 ± 2.7	15.4 ± 4.2
Vessel lengths in mm (%) ^d								
LMA	11 ± 5 (99)	12 ± 6 (100)	12 ± 4	11 ± 5		13 ± 6 (100)	9 ± 4 (100)	10 ± 3 (100)
LAD	130 ± 32 (96)	149 ± 25 (97)	67 ± 13	66 ± 12	134 ± 30 (96)	138 ± 39 (93)	114 ± 34 (77)	120 ± 26 (95)
LCX	97 ± 34 (93)	89 ± 30 (98)	55 ± 15	47 ± 10	83 ± 18 (98)	84 ± 34 (91)	83 ± 24 (72)	77 ± 23 (89)
RCA	148 ± 41 (82)	161 ± 38 (95)	123 ± 22	115 ± 28	121 ± 36 (98)	155 ± 41 (87)	115 ± 33 (71)	120 ± 32 (91)

CNR, contrast-to-noise ratio; EBT, electron-beam computed tomography; LMA, left main coronary artery; LAD, left anterior descending coronary artery; LCX, left circumflex coronary artery; RCA, right coronary artery

^aMRI and EBT studies were selected for comparative purposes

^bMultisegment reconstruction without β -blockade

^cMean ± standard deviation of the four main coronary vessels

^dProportion of the entire vessel length depicted free of motion artefacts where given

73% of the total artery length visualised could be depicted without motion artefacts [21], compared with $93 \pm 10\%$ on 16-slice scanners [20] (Table 3). This improvement was possible because of the higher temporal resolution resulting from faster gantry rotation and systemic heart rate control [20]. However, all but one study of MSCT summarised in Table 3 used pre-scan β -blockade. In our study, no β -blockers were given and the results obtained with multisegment reconstruction are comparable to those of previous studies investigating 16- and 64-slice CT (Table 3).

Diagnostic accuracy of multisegment reconstruction was superior to halfscan reconstruction, mainly because there were fewer correctly assessable vessels in halfscan reconstruction owing to the presence of more motion artefacts. Sensitivity and specificity rates of 92.5% and 78.0%, respectively, are similar to previously published pooled data (sensitivity of 95% and specificity of 69%) from studies on 16-slice scanners [29]. Most of these studies used systematic β -blockade to lower heart rates. We achieved similar results without β -blocker administration, indicating that the higher robustness of MSCT against motion artefacts can be attributed to the use of multisegment reconstruction. It is therefore expected that MSCT coronary angiography with multisegment reconstruction will be applicable to more patients, *e.g.* patients with bronchial asthma, who have contraindications to β -blockers. However, it must be borne in mind that the subgroup analysis already quoted showed that this higher robustness is also limited and that image quality and diagnostic accuracy are severely degraded at heart rates above 75 bpm. This appears to be the threshold up to which MSCT coronary angiography with multisegment reconstruction provides adequate diagnostic quality [16]. In patients with heart rates above 75 bpm, β -blockers will still be needed even if multisegment reconstruction is used.

CNRs were excellent with both multisegment and halfscan reconstructions and were higher than those previously published for electron beam tomography [21] and 4-slice [21] and 16 slice scanners [26] (Table 3). Multisegment reconstruction resulted in significantly higher mean CNRs than did halfscan reconstruction, but these differences are not clinically relevant.

Study limitations

An important disadvantage of multisegment reconstruction compared with halfscan reconstruction is the higher radiation exposure resulting from a lower pitch, which is necessary to assort images from multiple heartbeats. This is a cause of concern, but the calculated exposure of 12.2 ± 1.4 mSv [6] is still in the range reported for conventional coronary angiography in large non-selective studies [30, 31]. Tube current modulation is a promising technique and has been estimated to reduce radiation exposure by approximately 27% [32] to 45% [33] in patients with heart rates between 60 bpm and 70 bpm. This tool was not available when this study was performed. Although we used sophisticated criteria to measure vessel length and to identify motion artefacts, as did previous studies [15, 21, 28, 34], a subjective influence cannot be excluded. Interobserver variability

was not determined, as only one observer assessed image quality. Since then, 64-slice scanners [4, 8, 9, 28, 35, 36] and dual-source CT [37, 38] have become available and have been investigated in initial clinical studies as alternative approaches to shorten temporal resolution and improve diagnostic accuracy compared with 16-slice scanners. The effectiveness of multisegment reconstruction should also be investigated on those scanners.

Conclusions

Motion artefacts can be reduced significantly using multisegment reconstruction instead of standard halfscan reconstruction in a large consecutive group of patients without β -blocker administration to lower heart rates. This leads to higher image quality and better diagnostic accuracy in many patients, making CT easier to handle and applicable for patients with high heart rates (*e.g.* those that do not respond to β -blockers).

References

1. Nieman K, Cademartiri F, Lemos PA, Raaijmakers R, Pattynama PM, de Feyter PJ. Reliable noninvasive coronary angiography with fast submillimeter multislice spiral computed tomography. *Circulation* 2002;106:2051–4.
2. Ropers D, Baum U, Pohle K, Anders K, Ulzheimer S, Ohnesorge B, et al. Detection of coronary artery stenoses with thin-slice multi-detector row spiral computed tomography and multiplanar reconstruction. *Circulation* 2003;107:664–6.
3. Mollet NR, Cademartiri F, Nieman K, Saia F, Lemos PA, McFadden EP, et al. Multislice spiral computed tomography coronary angiography in patients with stable angina pectoris. *J Am Coll Cardiol* 2004;43:2265–70.
4. Ropers D, Rixe J, Anders K, Kuttner A, Baum U, Bautz W, et al. Usefulness of multidetector row spiral computed tomography with 64- x 0.6-mm collimation and 330-ms rotation for the noninvasive detection of significant coronary artery stenoses. *Am J Cardiol* 2006;97:343–8.
5. Dewey M, Hamm B. Cost effectiveness of coronary angiography and calcium scoring using CT and stress MRI for diagnosis of coronary artery disease. *Eur Radiol* 2007;17:1301–9.
6. Dewey M, Teige F, Schnapauff D, Laule M, Borges AC, Wernecke KD, et al. Noninvasive detection of coronary artery stenoses with multislice computed tomography or magnetic resonance imaging. *Ann Intern Med* 2006;145:407–15.
7. Kuettner A, Beck T, Drosch T, Kettering K, Heuschmid M, Burgstahler C, et al. Diagnostic accuracy of noninvasive coronary imaging using 16-detector slice spiral computed tomography with 188 ms temporal resolution. *J Am Coll Cardiol* 2005;45:123–7.
8. Mollet NR, Cademartiri F, van Mieghem CA, Runza G, McFadden EP, Baks T, et al. High-resolution spiral computed tomography coronary angiography in patients referred for diagnostic conventional coronary angiography. *Circulation* 2005;112:2318–23.
9. 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.
10. Schroeder S, Kopp AF, Kuettner A, Burgstahler C, Herdeg C, Heuschmid M, et al. Influence of heart rate on vessel visibility in noninvasive coronary angiography using new multislice computed tomography: experience in 94 patients. *Clin Imaging* 2002;26:106–11.

11. Burgstahler C, Beck T, Kuettner A, Reimann A, Kopp AF, Heuschmid M, et al. Image quality and diagnostic accuracy of 16-slice multidetector spiral computed tomography for the detection of coronary artery disease in elderly patients. *J Comput Assist Tomogr* 2005;29:734–8.
12. Flohr T, Ohnesorge B. Heart rate adaptive optimization of spatial and temporal resolution for electrocardiogram-gated multislice spiral CT of the heart. *J Comput Assist Tomogr* 2001;25:907–23.
13. Lembcke A, Rogalla P, Mews J, Blobel J, Enzweiler CN, Wiese TH, et al. Imaging of the coronary arteries by means of multislice helical CT: optimization of image quality with multisegmental reconstruction and variable gantry rotation time. *Röfo* 2003;175:780–5.
14. Blobel J, Baartman H, Rogalla P, Mews J, Lembcke A. Spatial and temporal resolution with 16-slice computed tomography for cardiac imaging. *Röfo* 2003;175:1264–71.
15. Dewey M, Laule M, Krug L, Schnapauff D, Rogalla P, Rutsch W, et al. Multisegment and halfscan reconstruction of 16-slice computed tomography for detection of coronary artery stenoses. *Invest Radiol* 2004;39:223–9.
16. Dewey M, Teige F, Laule M, Hamm B. Influence of heart rate on diagnostic accuracy and image quality of 16-slice CT coronary angiography: comparison of multisegment and halfscan reconstruction approaches. *Eur Radiol* 2007;17:2829–37.
17. Enzweiler CN, Kivelitz DE, Wiese TH, Taupitz M, Hohn S, Borges AC, et al. Coronary artery bypass grafts: improved electron-beam tomography by prolonging breath holds with preoxygenation. *Radiology* 2000;217:278–83.
18. Dewey M, Muller M, Teige F, Schnapauff D, Schink T, Hamm B, et al. Multisegment and halfscan reconstruction of 16-slice computed tomography for assessment of regional and global left ventricular myocardial function. *Invest Radiol* 2006;41:400–9.
19. Dewey M, Schnapauff D, Laule M, Lembcke A, Borges AC, Rutsch W, et al. Multislice CT coronary angiography: evaluation of an automatic vessel detection tool. *Röfo* 2004;176:478–83.
20. Ferencik M, Moselewski F, Ropers D, Hoffmann U, Baum U, Anders K, et al. Quantitative parameters of image quality in multidetector spiral computed tomographic coronary imaging with submillimeter collimation. *Am J Cardiol* 2003;92:1257–62.
21. Achenbach S, Giesler T, Ropers D, Ulzheimer S, Anders K, Wenkel E, et al. Comparison of image quality in contrast-enhanced coronary-artery visualization by electron beam tomography and retrospectively electrocardiogram-gated multislice spiral computed tomography. *Invest Radiol* 2003;38:119–28.
22. Chernoff DM, Ritchie CJ, Higgins CB. Evaluation of electron beam CT coronary angiography in healthy subjects. *AJR Am J Roentgenol* 1997;169:93–9.
23. Kim WY, Danias PG, Stuber M, Flamm SD, Plein S, Nagel E, et al. Coronary magnetic resonance angiography for the detection of coronary stenoses. *N Engl J Med* 2001;345:1863–9.
24. Giorgi B, Dymarkowski S, Maes F, Kouwenhoven M, Bogaert J. Improved visualization of coronary arteries using a new three-dimensional submillimeter MR coronary angiography sequence with balanced gradients. *AJR Am J Roentgenol* 2002;179:901–10.
25. Bogaert J, Kuzo R, Dymarkowski S, Beckers R, Piessens J, Rademakers FE. Coronary artery imaging with real-time navigator three-dimensional turbo-field-echo MR coronary angiography: initial experience. *Radiology* 2003;226:707–16.
26. Kefer J, Coche E, Legros G, Pasquet A, Grandin C, Van Beers BE, 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;46:92–100.
27. Dewey M, Teige F, Schnapauff D, Laule M, Borges AC, Rutsch W, et al. Combination of free-breathing and breath-hold steady-state free precession magnetic resonance angiography for detection of coronary artery stenoses. *J Magn Reson Imaging* 2006;23:674–81.
28. Ferencik M, Nomura CH, Maurovich-Horvat P, Hoffmann U, Pena AJ, Cury RC, et al. Quantitative parameters of image quality in 64-slice computed tomography angiography of the coronary arteries. *Eur J Radiol* 2006;57:373–9.
29. Hamon M, Morello R, Riddell JW. Coronary arteries: diagnostic performance of 16- versus 64-section spiral CT compared with invasive coronary angiography—meta-analysis. *Radiology* 2007;245:720–31.
30. Cusma JT, Bell MR, Wondrow MA, Taubel JP, Holmes DR Jr. Real-time measurement of radiation exposure to patients during diagnostic coronary angiography and percutaneous interventional procedures. *J Am Coll Cardiol* 1999;33:427–35.
31. Zorzetto M, Bernardi G, Morocutti G, Fontanelli A. Radiation exposure to patients and operators during diagnostic catheterization and coronary angioplasty. *Cathet Cardiovasc Diagn* 1997;40:348–51.
32. Gerber TC, Stratmann BP, Kuzo RS, Kantor B, Morin RL. Effect of acquisition technique on radiation dose and image quality in multidetector row computed tomography coronary angiography with submillimeter collimation. *Invest Radiol* 2005;40:556–63.
33. Trabold T, Buchgeister A, Kuttner M, Heuschmid A, Kopp S, Schroder C, et al. Estimation of radiation exposure in 16-detector row computed tomography of the heart with retrospective ECG-gating. *Röfo* 2003;175:1051–5.
34. Taupitz M, Schnorr J, Wagner S, Kivelitz D, Rogalla P, Claassen G, et al. Coronary magnetic resonance angiography: experimental evaluation of the new rapid clearance blood pool contrast medium P792. *Magn Reson Med* 2001;46:932–8.
35. Leschka S, Alkadhi H, Plass A, Desbiolles L, Grunenfelder J, Marincek B, et al. Accuracy of MSCT coronary angiography with 64-slice technology: first experience. *Eur Heart J* 2005;26:1482–7.
36. Leber AW, Knez A, Ziegler F, Becker A, Nikolaou K, Paul S, et al. Quantification of obstructive and nonobstructive coronary lesions by 64-slice computed tomography: a comparative study with quantitative coronary angiography and intravascular ultrasound. *J Am Coll Cardiol* 2005;46:147–54.
37. Flohr TG, McCollough CH, Bruder H, Petersilka M, Gruber K, Suss C, et al. Ohnesorge, First performance evaluation of a dual-source CT (DSCT) system. *Eur Radiol* 2006;16:256–68.
38. Scheffel H, Alkadhi H, Plass A, Vachenaue R, Desbiolles L, Gaemperli O, et al. Accuracy of dual-source CT coronary angiography: first experience in a high pre-test probability population without heart rate control. *Eur Radiol* 2006;16:2739–47.