Evaluation of CT coronary artery angiography with 320-row detector CT in a high-risk population

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Objectives: The aim of this article was to prospectively evaluate the accuracy and radiation dose of 320-detector row dynamic volume CT (DVCT) for the detection of coronary artery disease (CAD) in a high-risk population.

Methods: 60 patients with a high risk of CAD underwent DVCT without preceding heart rate control and also underwent invasive coronary angiography (ICA), which served as the standard reference.

Results: On a per segment analysis, overall sensitivity was 95.3%, specificity was 97.6%, positive predictive value was 90.6%, negative predictive value was 98.8% and Youden index was 0.93. In both heart rate subgroups, diagnostic accuracy for the assessment of coronary artery stenosis was similar. The accuracy of the subgroup with an Agatston score ≥ 100 was lower than that for patients with an Agatston score < 100 . However, the difference between DVCT and ICA results was not significant ($p=0.08$). The mean estimated effective dose of CT was 12.5 ± 9.4 mSv. In those patients with heart rates less than 70 beats per minute (bpm), the mean radiation exposure of DVCT was 5.2 ± 0.9 mSv. The effective radiation dose was significantly lower than that of ICA (14.1 ± 5.9 mSv) ($p<0.001$). When the heart rate was > 70 bpm, a significantly higher dose was delivered to patients with DVCT (22.6 ± 5.2 mSv, $p<0.001$) than with ICA (15.0 ± 5.3 mSv, $p<0.001$).

Conclusion: DVCT reliably provides high diagnostic accuracy without heart rate/rhythm control. However, from a dosimetric point of view, it is recommended that heart rate should be controlled to < 70 bpm to decrease radiation dose.

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The small diameter of the coronary segments, their complex three-dimensional geometry and their rapid movement throughout the cardiac cycle represent the major challenges for artefact-free coronary CT angiography (CTA). With each scanner generation, motion artefacts re-appear as a major cause of image quality degradation during coronary CTA [1–10]. Coronary CTA studies of each coronary artery with four-multidetector CT (MDCT) at a gantry rotation time of 500 ms had significantly decreased image quality with increasing mean heart rates [3]. Using 16-MDCT at a gantry rotation time of 420 ms, Hoffmann et al [2] found a significant negative correlation between overall image quality and mean heart rate. Even using 64-section CT, with its gantry rotation speed of 330 ms, elevated and irregular heart beats were found to cause relevant degradation of image quality [1, 4, 9, 11]. Using dual-source CT (DSCT) with an increased temporal resolution of 83 ms, there was no significant correlation between mean heart rate and the overall image quality for any coronary segment or for any individual coronary artery. Nonetheless, irregular heart rates still slightly affect the image quality of non-invasive coronary angiography, even with DSCT [10, 12].

The 320-detector row dynamic volume CT (DVCT) is characterised by 320 slice detectors with a thickness of 0.5 mm and gantry rotation time of 350 ms. With a wide coverage of 16 cm in the z-axis, the whole heart can be covered within one cardiac cycle. Theoretically, DVCT makes it possible to scan patients with an irregular heart rate without “stair-step” artefacts. At the same time, DVCT avoids the overlapping rotations of helical CT, and the application of prospective echocardiogram (ECG) gating has become more feasible. Recent studies of DVCT have mainly been based on a low heart rate [13–17]. Few studies have investigated the diagnostic accuracy in higher heart rates and arrhythmia. Our purpose was to systematically evaluate the diagnostic accuracy and exposure dose of DVCT in a high-risk population with high and irregular heart rates.

Methods and materials

Ethical issues

The study protocol was approved by the local ethics committee; the main issues taken into consideration were the radiation dose and risk of iodine contrast media. Written informed consent was obtained from all patients [18].

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Patients

Between December 2008 and June 2009, we prospectively enrolled 79 patients who had a high risk of coronary artery disease (CAD) according to the Morise Standard [19]. Exclusion criteria were as follows: allergy to iodinated contrast agents ($n=4$), renal insufficiency (creatinine level $>120 \mu\text{mol l}^{-1}$, $n=2$), pregnancy ($n=2$), haemodynamic instability ($n=2$) and abnormal origin and course of the coronary arteries ($n=2$). Patients who underwent stent graft and bypass surgery ($n=5$) were excluded from this study. After exclusion of 17 patients for the above-mentioned exclusion criteria and 2 patients who could not be enrolled because of refusal or withdrawal of consent, the final study group included 60 patients (22 women, 38 men; mean age, 68 ± 9 years; age range, 38–83 years) (Table 1).

At the time of CT, 31 patients (51.7%) were taking the following oral negative chronotropic drugs as part of their baseline medication: the β -receptor antagonists atenolol (mean daily dose, 69 ± 21 mg; range, 50–100 mg) in 12 cases, metoprolol (mean daily dose, 187 ± 73 mg; range, 100–300 mg) in 13 cases and the calcium channel blocker amlodipine (mean daily dose, 6 ± 4 mg; range, 5–10 mg) in 6 cases. The reasons for medication were management of arterial hypertension and long-term management of angina pectoris. No additional β -blockers were administered before CT.

CT angiography

Initially, patients were submitted to two CT tests (coronary calcium scoring and CTA) using DVCT (Aquilion One; Toshiba, Nasu, Japan). Calcium scoring was performed using prospective ECG gating with 400 ms gantry rotation, 120 kV tube voltage and 300 mA tube current. For CTA, no drugs were administered to control the patient's heart rate, but all patients received 0.4 mg of nitroglycerin sublingually 2 min before scanning (contraindications were hypotension, current use of nitrate medications and nitrate-sensitive migraine). Scanning was performed from the level of the tracheal bifurcation to the diaphragm to image the entire heart (scanning range coverage was 12–14 cm). A 50–65 ml bolus of iohexol (Omnipaque 350; Amersham Health, Shanghai,

China) was injected into an antecubital vein through an 18-gauge catheter with an injection rate of 5.5 ml s^{-1} followed by 50 ml of saline continuously.

The enhancement scan was controlled by means of bolus tracking (SureStart; Toshiba). The trigger threshold, located in the descending aorta at the same level as the aorta root, was set at 180 HU. Scanning parameters were as follows: detector collimation, 320×0.5 mm; gantry rotation time, 350 ms; tube current, 350–500 mA; and tube voltage, 100–120 kV. If the patient's body mass index (BMI) was <18 , 100 kV and 350 mA was used; if the patient's BMI was between 18 and 24, 100 kV and 400 mA was used; if the patient's BMI was >24 , 120 kV and 450–500 mA was used.

Data acquisition was performed using prospective ECG gating from 60 to 85% of the R–R interval when the heart rate did not exceed 70 beats per minute (bpm), 40–85% in patients with heart rate between 70 and 80 bpm and 30–90% in patients with heart rate >80 bpm.

The ECG was digitally recorded during data acquisition and was stored for further data processing.

Reconstruction and post-processing

Image reconstruction was performed with 0.5 mm slice thickness and 0.25 mm overlap. Images were reconstructed at a preset of 75% of the R–R interval. When the image quality was poor in patients with a stable heart rate, we determined which image from the automatically generated data stack at 75% of the R–R interval had the worst image quality. At this fixed level we then undertook further reconstructions at 2% steps through the available reconstruction window to determine the optimal reconstruction interval. For patients with an unstable heart rate, we used an absolute timing approach and reconstructed transverse images with a 10-ms step from the peak R wave. In both cases, when the interval with least motion artefact was determined, the whole heart data were reconstructed. All reconstructed images were transferred to an independent workstation (Vitrea II FX; Vital Images, Minnetonka, MN). Multiplanar reconstruction, curve-planar reconstruction, volume rendering and vessel analysis were performed on the workstation to assess stenosis.

Image analysis

Coronary segments were defined according to American Heart Association guidelines [20], and all segments with a diameter of at least 1.5 mm at their origin were included. The calcium score was calculated for non-enhanced images using the Agatston score. All reconstructed images were evaluated and classified by two independent assessors (one with 7 years and one with 3 years of experience in cardiovascular radiology). Image quality was assessed according to four levels: Grade 1, no artefacts and clear delineation of the segment; Grade 2, minor artefacts and mild blurring of the segment; Grade 3, moderate artefacts and moderate blurring; Grade 4, severe artefacts and segment too poor for evaluation. The extent of vessel stenosis was classified as follows: atherosclerosis with stenosis $<50\%$ and stenosis $>50\%$. Consensus agreement was used for any disagreements.

Table 1. Demographic data presented as number, means $\pm$ standard deviation or absolute number (percentage)

Number of patients	60
Age	68 ± 9
Male	38 (63.3)
Female	
Pre-menopausal	8 (13.3)
Post-menopausal	14 (23.3)
Typical angina	40 (66.7)
Hypertension	44 (73.3)
Diabetes	14 (23.3)
Smoking	26 (43.3)
Family history of CAD	20 (33.3)
Hyperlipidaemia	34 (56.7)
BMI (weight/height ²)	22.1 ± 5.7
Morise scoring	18.3 ± 5.5

BMI, body mass index; CAD, coronary artery disease.

Evaluation of radiation dose of CT coronary angiography and invasive coronary angiography

The dose-length product (DLP) displayed on the dose report on the CT scanner was recorded. An effective dose (E) was obtained using the equation $E=k \times \text{DLP}$ ($k=0.029 \text{ mSv mGy}^{-1} \text{ cm}^{-1}$, which was calculated specifically for DVCT) [21]. For ICA, the effective dose was estimated as a product of the dose-area product of the diagnostic coronary scenes multiplied by a conversion factor ($k=0.22 \text{ mSv mGy cm}^2$) [22].

Invasive coronary angiography

Cardiac angiograms were performed using the conventional Judkin technique [23]. Four views of the left coronary artery and two views of the right coronary artery (RCA) were analysed in consensus by two cardiologists (one with 6 years and one with 7 years of experience). They were blinded to the CT results during analysis. Quantitative assessment of stenosis severity on angiograms was performed with the same criteria as those used for the CT data.

Statistical analysis

Statistical analysis was performed using SPSS software [SPSS v.12 for Windows; IBM Corporation (formerly SPSS Inc.), Armonk, NY]. Quantitative variables were expressed as means $\pm$ standard deviations or median (interquartile range). Categorical variables were expressed as frequencies or percentages.

Anatomical variants, segments with vessel diameter $<1.5 \text{ mm}$, were excluded from analysis [24]. Similar to a previous publication, non-evaluative segments were considered as positive findings, because every patient with a non-evaluative segment would undergo ICA in clinical practice [25].

Consistency testing to evaluate whether there was any difference between the two evaluators was carried out using the kappa statistic.

An average heart rate of $<70 \text{ bpm}$ was defined as a low heart rate, and a heart rate of $\geq 70 \text{ bpm}$ was defined as a high heart rate for the purposes of evaluation of the acquisition technique. A calcium score of <100 was defined as a low score and a calcium score of ≥ 100 was defined as a high score for the purposes of evaluating the effect of the calcium score on image quality and diagnostic accuracy. The result of ICA was used as the reference standard to calculate the sensitivity, specificity, positive predictive value (PPV) and negative predictive value (NPV) of CTA. The influence of heart rate and calcium score was evaluated using the binominal distribution test to calculate the 95% confidence interval [26]. The McNemar test was performed for both CTA and ICA results. The Fisher exact probability test was used to evaluate the concordances for groups based on heart rate ($<70 \text{ vs } \geq 70 \text{ bpm}$) and calcium score ($<100 \text{ vs } \geq 100$) in CTA. The paired t -test was performed to evaluate the radiation exposure between CTA and ICA. The effects of heart rate on radiation exposure were evaluated by independent samples t -test. The critical value for p was defined as <0.05 to indicate a statistically significant result.

Results

Heart rate and calcium score

All 60 patients completed CTA and ICA examinations successfully. The mean heart rate during CT scan was $73.7 \pm 15.4 \text{ bpm}$ (range 51–128 bpm); 34 (56.7%) patients had heart rates of $<70 \text{ bpm}$ (average, $63.9 \pm 4.7 \text{ bpm}$; range, 51–68 bpm) and 26 (43.3%) patients had heart rates of $\geq 70 \text{ bpm}$ (average, $86.5 \pm 15.1 \text{ bpm}$; range, 73–128 bpm). 52 (86.7%) patients had coronary arterial calcification. The median calcium score per patient was 653 (interquartile range 413–1949) and the median calcium score per segment was 74 (interquartile range 41–222). 588 (68%) segments had a calcium score <100 , median 31 (interquartile range 12–65); 278 (32%) segments had a calcium score ≥ 100 , median 213 (interquartile range 134–276).

Table 2. Image quality and accuracy of diagnosis by heart rate groups or Agatston calcium score groups

Total	Heart rate			Agatston calcium score	
		$<70 \text{ bpm}$	$\geq 70 \text{ bpm}$	<100	≥ 100
Number of segments	866	510	356	588	278
Image quality					
Grade 1	72.5% (628/866)	74.9% (382/510)	70.5% (246/356)	86.4% (508/588)	43.2% (120/278)
Grade 2	20.0% (173/866)	19.0% (97/510)	22.0% (76/356)	10.7% (63/588)	39.5% (110/278)
Grade 3	5.4% (47/866)	4.1% (21/510)	7.5% (26/356)	2.9% (17/588)	10.8% (30/278)
Grade 4	2.1% (18/866)	2.0% (10/510)	7.5% (8/356)	0% (0/588)	6.5% (18/278)
Sensitivity	95.3% (164/172)	95.7% (111/116)	94.6% (53/56)	96.9% (62/64)	94.4% (102/108)
(95% CI)	(91.04%, 97.97%)	(90.23%, 98.59%)	(85.13%, 98.88%)	(89.16%, 99.62%)	(88.30%, 97.93%)
Specificity	97.6% (677/694)	98.0% (386/394)	97.0% (291/300)	99.6% (522/524)	91.1% (155/170)
(95% CI)	(96.11%, 98.57%)	(96.04%, 99.12%)	(94.38%, 98.62%)	(98.63%, 99.95%)	(85.86%, 94.98%)
PPV	90.6% (164/181)	93.3% (111/119)	85.5% (53/62)	96.9% (62/64)	87.2% (102/117)
(95% CI)	(85.39%, 94.43%)	(87.18%, 97.05%)	(74.22%, 93.14%)	(89.16%, 99.62%)	(79.74%, 92.64%)
NPV	98.8% (677/685)	98.7% (386/391)	99.0% (291/294)	99.6% (522/524)	96.3% (155/161)
(95% CI)	(97.71%, 99.49%)	(97.04%, 99.58%)	(97.05%, 99.79%)	(98.63%, 99.95%)	(92.07%, 98.62%)
Youden index	0.93	0.94	0.92	0.97	0.86

bpm, beats per minute; CI, confidence interval; NPV, negative predictive value; PPV, positive predictive value.

Figure 1. Male patient, aged 70 years, heart rate 51 beats per minute, 75% phase reconstruction images. (a) Volume rendering and (b) curve-planar reconstruction demonstrated severe calcified plaque in the lumens of the proximal and middle sections of the left anterior descending coronary artery; Agatston calcium scores were 361 and 235. Arrows indicate stenosis of the arteries. (c) Invasive coronary angiography showed severe luminal stenosis at the proximal and middle sections of left anterior descending coronary artery.

Image reconstruction and image quality

Theoretically, there are 15 segments per patient, giving a total of 900 coronary arterial segments in 60 patients. However, 34 segments were not visualised or the initial diameter of the segment was less than 1.5 mm; therefore, only 866 segments were available for analysis.

The image quality grades of these segments were: Grade 1, 72.5% (628/866); Grade 2, 20.0% (173/866); Grade 3, 5.4% (47/866); Grade 4, 2.1% (18/866) (Table 2). 18 segments were evaluated as Grade 4 because of severe calcification, with a calcium score greater than 220 (Figure 1). Between-rater concordance was fair ($\kappa=0.71$).

For 30 patients in sinus rhythm and 4 patients with arrhythmia in the heart rate <70 bpm group, and 10 patients in sinus rhythm in the heart rate ≥ 70 bpm group, image quality was optimal when reconstructed at the preset 75% interval. Images of 9 patients from the high heart rate group were reconstructed from selected multiphase R-R interval images using either a relative or absolute timing approach (42% phase, $n=3$; 50% phase,

$n=4$; 350 ms, $n=2$). One patient required different phase selections for different vessels [RCA, 40% phase; left anterior descending coronary artery, left circumflex (LCX), 70% phase]. Six patients with arrhythmias required reconstruction by absolute timing at 280, 310, 350, 400, 420 and 450 ms after the R wave, respectively.

In the group with an Agatston calcium score ≥ 100 , there were 120 segments with Grade 1 image quality, of which 28.3% (34/120) required reconstruction from different phases owing to the calcification artefacts on the wall of the vessel.

Radiation exposure

The mean estimated effective dose of DVCT was 12.5 ± 9.4 mSv. In the patients with a heart rate of <70 bpm (BMI 23.7 ± 4.1), the mean radiation exposure of coronary CTA was 5.2 ± 0.9 mSv. According to the paired t -test, the effective radiation dose was significantly lower than that of ICA (14.1 ± 5.9 mSv) ($p < 0.001$). When the heart rate was

Figure 2. Male patient, aged 74 years, heart rate 87 beats per minute, 42% phase reconstruction images. (a) Volume rendering and (b) curve-planar reconstruction demonstrated non-calcified plaque in the left anterior descending coronary artery. (c) Invasive coronary angiography showed severe luminal stenosis in the same sections of the left anterior descending coronary artery.

Figure 3. Female patient, aged 83 years, heart rate 57 beats per minute, 75% phase reconstruction images. Volume rendering (a) and curve-planar reconstruction (b) demonstrated complex plaque in the middle section of the right coronary artery (RCA); Agatston calcium score was 126. Invasive coronary angiography (c) showed severe luminal stenosis at the same sections of the RCA.

>70 bpm (BMI 23.9 ± 3.3), a significantly higher dose was delivered to patients (22.6 ± 5.2 mSv, $p < 0.001$). In addition, the exposure dose was significantly higher than that of ICA (15.0 ± 5.3 mSv, $p < 0.001$).

The diagnostic accuracy of DVCT for coronary arterial stenosis

There was good interrater concordance between the two radiologists ($\kappa = 0.86$). In the ICA data, there were 46 patients, 98 coronary artery branches and 154 segments with stenosis >50%. Among them, 16 (26.7%) cases of stenosis were located in 1 branch, 8 (13.3%) were located in 2 branches and 22 (36.7%) were located in 3 branches. The other 14 cases (23.3%) did not show stenosis >50%.

Among the 172 stenotic segments proven by ICA, DVCT diagnosed 164 cases accurately (Figures 2 and 3). Among the 694 segments which were proven to have no significant stenosis by ICA, DVCT diagnosed 677 cases accurately. Thus, there were 164 true positives, 677 true negatives, 8 false negatives (FNs) and 17 false positives (FPs). Of the 17 FP cases, 15 were due to calcification artefacts and 2 were due to motion artefacts. Of the eight FN cases, five were due to calcification and three were due to motion artefacts.

For the 866 segments evaluated, the sensitivity of DVCT was 95.3%; specificity, 97.6%; PPV, 90.6%; NPV, 98.8%; and Youden index, 0.93. The McNemar test showed no statistical significance for the diagnostic result between DVCT and ICA ($p = 0.11$).

For both the 510 segments with heart rate <70 bpm and the 356 segments with heart rate ≥ 70 bpm, there was no statistically significant difference between the CTA and ICA results ($p = 0.58, 0.15$). For both the 588 segments with an Agatston calcium score <100 and the 278

segments with an Agatston calcium score ≥ 100 , there was no statistically significant difference between CTA and ICA ($p = 1.0, 0.08$) (Table 2).

DVCT diagnosed one FP case of LCX plaque with approximately 50% partial lumen stenosis, whereas that segment in ICA appeared unremarkable (Table 3). There was no significant difference between DVCT and ICA (per vessel level, $p = 1.0$; per patient level, $p = 1.0$).

There was no statistical difference in concordance between ICA and CTA for the two heart rate groups ($p = 0.54$); there was, however, a statistically significant difference ($p < 0.001$) for the diagnosis in the two Agatston score groups (Table 4).

Discussion

The advantage of DVCT over coronary artery angiography

The quality of coronary artery imaging has been improved with the development of high-resolution CT equipment. For best imaging, stable sinus rhythm and an average heart rate <70 bpm is preferred [9, 27–29]. When the heart rate is fast and unstable, there may be CT image artefacts due to table movement and data registration errors in helical data assimilation mode [9, 30]. Clinically, a β -blocker is often administered to lower the heart rate for better image quality, but this is ineffective in about 20% of patients and may have adverse effects [27, 28]. Dual-source CT has improved temporal resolution drastically [25]. Still, it has limited z-axis coverage and does not yet achieve complete volumetric scanning. DVCT scanners have 0.5 mm detectors in each of the 320 slices, with a rotation speed of 350 ms, giving coverage of 16 cm per rotation. For DVCT, at the periphery of the

Table 3. Dynamic volume CT evaluation on per vessel and per patient levels

	Sensitivity (%)	Specificity (%)	PPV (%)	NPV (%)
Per vessel level	100 (70/70)	99.1 (109/110)	98.6 (70/71)	100 (109/109)
Per patient level	100 (46/46)	92.9 (13/14)	97.9 (46/47)	100 (13/13)

NPV, negative predictive value; PPV, positive predictive value.

Table 4. Comparison of the correlation rate of different heart rates and calcium scoring

	Correlated	Not correlated	p-value
Heart rate			
<70 bpm	497	13	0.54
≥70 bpm	344	12	
Agatston calcium scoring			
<100	584	4	<0.001
≥100	257	21	

bpm, beats per minute.

coverage field, image quality can be inferior because the design of the instrument means that data are collected from a conical volume. However, the scanning range needed in our study was 12–14 cm and the coverage available within the cone still enables whole heart coverage within one heart beat [21]. Whole organ acquisition within one rotation allows the contrast bolus to be imaged at a single time point. The single rotation acquisition eliminates helical and “stair-step” artefacts.

The effect of heart rate and calcification on diagnosis

In ideal heart rate conditions, the whole heart scan can be finished within one cardiac cycle. For patients with higher heart rates when better temporal resolution is desired, multisegment reconstruction is necessary and two or more heart beat acquisition may be needed. In our study, if the heart rate was <70 bpm at the time of breath-hold practice, image acquisition was manually adjusted using one heart beat scan acquisition mode. For heart rates between 70 and 80 bpm, two heart beat acquisition mode was used. For heart rates >80 bpm, three or four heart beat acquisition mode was necessary to increase temporal resolution and to obtain adequate image quality. Using multiheart beat acquisition mode, the temporal resolution could reach between 87.5 and 43.8 ms. However, the multiheart scanning mode inevitably increases the exposure dose, as the scanning time is increased. In 64-MDCT, the detector range in the z-axis covers only up to 4 cm. To image an entire heart using a 64-MDCT, helical scanning mode is usually used. However, no two cardiac cycles are completely identical because of intercycle variability in the heart rate. The commonly applied ECG-gating image reconstruction technique does not generate images in exactly corresponding cardiac phases because of

non-proportional shortening and prolongation of the cardiac phases at different heart rates. Misregistration artefacts of the so-called “stair-step” type cannot be completely avoided. In addition, there may be images with gaps in the image plane in subjects with arrhythmias [13, 16] (Figure 4). Recently, step-and-shoot coronary CTA has gained renewed interest to reduce radiation exposure. However, it has more strict preconditions that heart rates should be low and regular [31]. To overcome these problems, it is necessary to image the entire heart in a single cardiac cycle. DVCT allows the whole coronary arteries to be imaged at the same phase. There is no need to piece together image subvolumes, which makes it possible to scan patients with arrhythmias or heart rate irregularities with minimal/no “stair-step” artefacts [13–17]. The software predicts intervals to acquire data based on previous cardiac cycles so, if the difference between cardiac phases is slight, the image quality is acceptable. If the heart rate changes more than 20% from the previous pattern collected during breath-holding, the DVCT software will assume an arrhythmic heart beat has occurred and the scanner will hold on exposure. The system will then capture one normal beat until the maximum exposure time is reached (Figure 5).

In our study, we concluded that DVCT has high accuracy for coronary artery stenosis in patients with a high heart rate and arrhythmias. Although heart rates ≥70 bpm could cause mild to moderate motion artefacts, the long coverage in the z-axis, with multisegment reconstruction techniques, allows image quality to be improved drastically. Comparing patients with lower and higher heart rates, there is no significant difference in diagnostic accuracy. In previous studies, calcified plaques were the most significant factors influencing diagnostic accuracy and CT image quality [32]. This study shows that image quality in segments with an Agatston calcium score ≥100 is poorer than in segments with an Agatston score <100 with a resultant minor reduction in diagnostic accuracy. However, statistical analysis showed no significant difference between the results of DVCT and ICA in the Agatston score ≥100 group. This is because the single gantry rotation (non-helical scan) reduced the development of “bloom” artefacts around heavily calcified plaques, allowing 98% of segments to be evaluated. We also found 18 segments that were of image quality Grade 4 owing to severe calcification. Therefore, severe calcification remains a factor compromising the diagnostic utility of DVCT.

Figure 4. For traditional helical CT, the entire heart is imaged by subvolumes of the entire cardiac volume over multiple gantry rotations. If arrhythmia happens, no two cardiac cycles are completely the same. The “stair-step” artefacts cannot be completely avoided. There would be images with gaps in the image plane in subjects with arrhythmias. For arrhythmias, slow pitch is needed. However, overlapping exposures to the patient come at the cost of a higher radiation dose.

Figure 5. For dynamic volume CT (DVCT), there is no need to piece together image subvolumes. This can be clearly appreciated in so-called “stair-step” artefacts due to multiple gantry rotations. At the same time, DVCT avoids the overlapping rotations for helical cardiac CT and the application of prospective echocardiogram gating has become more feasible.

Clinical implications of DVCT

The rapid development of coronary CTA has helped to exclude the presence of significant CAD. However, the rapid increase in CT examinations has raised concern about the increasing radiation exposure to patients [33, 34]. The ECG gating in coronary CTA improved from retrospective without dose modulation, to retrospective with dose modulation and, further, to prospective mode, which decreased the radiation dose significantly. However, patients with irregular heart rates are not eligible for prospective ECG gating, because the different R–R intervals preclude reliable simultaneous registration of image data with the desired cardiac phases [35]. To overcome these problems, it is necessary to image the entire heart at the same time.

For calculation of the effective dose, the following equation was used: $E = k \times \text{DLP}$. The value of $k = 0.017 \text{ mSv mGy}^{-1} \text{ cm}^{-1}$ [13, 36] was usually used in previous studies. However, this conversion factor is the chest conversion factor. Recent studies have suggested that the conversion factor (k) changes with organ, scanning mode, patient size, X-ray tube voltage and other factors [21, 37]. In our study, we used the results of Einstein et al [21], who calculated the conversion factor of DVCT using volume mode and standard exposure time to be $0.029 \text{ mSv mGy}^{-1} \text{ cm}^{-1}$ [21].

Study of DSCT and 64-multislice CT with a heart rate $<65 \text{ bpm}$ and $k = 0.017 \text{ mSv mGy}^{-1} \text{ cm}^{-1}$ revealed exposure doses of $10.9 \pm 1.1 \text{ mSv}$ and $10.4 \pm 1.7 \text{ mSv}$, respectively [36], which were significantly higher than those of DVCT with a heart rate of $<70 \text{ bpm}$ ($5.2 \pm 0.9 \text{ mSv}$). This may be explained as follows. Helical cardiac CT imaging requires table movement that transports the patient through the projection of an X-ray beam. Overlapping exposures to the patient come at the cost of a higher radiation dose (Figure 4). DVCT, with full cardiac coverage, does not require an overlapping radiation exposure and provides significant radiation dose savings for cardiac imaging (Figure 5). When the heart rate was $<70 \text{ bpm}$, the dose of DVCT was even lower than that of ICA. However, using DVCT, the dose increases significantly in higher heart rates as multiheart beats are needed during scanning.

A recent study of DSCT using the spiral Flash mode reported the radiation dose to be $1.0 \pm 0.3 \text{ mSv}$ in patients with stable low heart rates [38]. The difference may be because the heart rates in our study were not always regular. If an arrhythmia occurred, one extra heart beat acquisition was needed, which increased the scanning time. Second, the ECG-triggered phase was different. As

the heart rate was $<60 \text{ bpm}$ in the Lell et al [38] study, the triggered phase was preset at only at 60%, which resulted in a shorter scanning time. Third, the conversion factor used was not the same. The difference requires further study.

Of those patients undergoing ICA in a European series in 1995, only 28% required an intervention or bypass grafting [39]. Our study shows that DVCT has very high NPV with only eight FN cases, including five cases of calcified artefacts and three cases of arrhythmia. When there is no significant calcification and a regular heart rate, DVCT could therefore be applied to rule out indications for interventions or bypass grafting. In the previous studies, CTA was proven to be effective for diagnosis of coronary artery stenosis in low-, medium- and high-risk populations [25, 32, 40]. This study shows that, without heart rate control, the accuracy of DVCT in the diagnosis of coronary stenosis in a high-risk population is still high. It is likely that the accuracy of DVCT would be higher in low- and medium-risk groups with lower degrees of calcification.

Limitations

First, the image quality scoring might have been influenced by a subjectivity bias; second, as prospective ECG gating was used to reduce the radiation dose, the optimal phase for reconstruction can be missed; third, the disadvantage of the prospective ECG-gating technique is that cardiac function cannot be assessed.

In conclusion, DVCT reliably provides high diagnostic accuracy without heart rate/rhythm control. However, from a dosimetric point of view, it is recommended that the heart rate should be controlled to $<70 \text{ bpm}$ to decrease the radiation dose.

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