

Influence of image acquisition settings on radiation dose and image quality in coronary angiography by 320-detector volume computed tomography: the CORE320 pilot experience

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Abstract

The objective of this study was to investigate the impact of image acquisition settings and patients' characteristics on image quality and radiation dose for coronary angiography by 320-row computed tomography (CT). CORE320 is a prospective study to investigate the diagnostic performance of 320-detector CT for detecting coronary artery disease and associated myocardial ischemia. A run-in phase in 65 subjects was conducted to test the adequacy of the computed tomography angiography (CTA) acquisition protocol. Tube current, exposure window, and number of cardiac

beats per acquisition were adjusted according to subjects' gender, heart rate, and body mass index (BMI). Main outcome measures were image quality, assessed by contrast/noise measurements and qualitatively on a 4-point scale, and radiation dose, estimated by the dose-length-product. Average heart rate at image acquisition was 55.0 ± 7.3 bpm. Median Agatston calcium score was 27.0 (interquartile range 1-330). All scans were prospectively triggered. Single heart beat image acquisition was obtained in 61 of 65 studies (94%). Sixty-one studies (94%) and 437 of 455 arterial segments (96%) were of diagnostic image quality. Estimated radiation dose was significantly greater in obese (5.3 ± 0.4 mSv) than normal weight (4.6 ± 0.3 mSv) or overweight (4.7 ± 0.3 mSv) subjects ($P < 0.001$). BMI was the strongest factor influencing image quality (odds ratio=1.457, $P=0.005$). The CORE320 CTA image acquisition protocol achieved a good balance between image quality and radiation dose for a 320-detector CT system. However, image quality in obese subjects was reduced compared to normal weight subjects, possibly due to tube voltage/current restrictions mandated by the study protocol.

one second. Such short image acquisition allows the use of smaller contrast volumes,¹⁰ lower radiation doses to the patient,^{2,6,11} and the inclusion of patient populations previously considered unsuitable for CTA imaging such as patients with cardiac arrhythmias.¹² The exposure to ionizing radiation and the associated risk of cancer is an important limitation of CT imaging.^{4,11,13-14} Currently, there are no federal or state regulations for acceptable radiation doses for CTA examinations; however, operators are urged to adhere to the ALARA (as low as reasonably achievable) principle. The challenge to clinicians is, therefore, to find the right balance between acceptable image quality and the lowest radiation dose for each individual patient. The purpose of this study was to investigate the impact of 320-slice scan acquisition settings for a representative patient population on radiation dose and image quality. This may guide clinicians and researchers in identifying the most appropriate protocol using a 320-detector system.

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Key words: CT angiography, image acquisition, image quality, radiation dose, body mass index, contrast to noise ratio.

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Introduction

CT coronary angiography (CTA) has in the past years become a standard approach in the non-invasive assessment of coronary arteries.¹⁻⁵ A recently introduced 320-row CT scanner has a detector width of 16 cm enabling the acquisition of a full cardiac CT dataset within a single heartbeat.⁶⁻⁹ Compared to a 64-slice system, image acquisition time is reduced from approximately 8-12 s to less than

Materials and Methods

Study population

The coronary evaluation using 320-detector computed tomography (CORE320) study is a prospective, multicenter, international study involving 16 hospitals in 8 countries (the US, Brazil, Canada, Singapore, Japan, Germany, Denmark and the Netherlands) designed to evaluate the diagnostic accuracy of 320-row detector CT to detect coronary artery luminal stenoses and corresponding myocardium perfusion defects in subjects with suspected coronary artery disease, compared to single photon

emission computed tomography (SPECT) and conventional coronary angiography. Before starting enrollment, a run-in phase was conducted for which each participating hospital provided at least three clinical CTA studies following the CORE320 acquisition protocol. Exclusion criteria included contraindications to iodine contrast material, renal insufficiency (serum creatinine >1.5 mg/dL or calculated creatinine clearance of <60 mL/min), atrial fibrillation, tachyarrhythmia, advanced atrioventricular block, symptomatic heart failure, previous coronary artery bypass or cardiac surgery, coronary intervention within the last six months, intolerance of beta blockers, and severe pulmonary disease. The main purpose of this run-in phase was to test adherence to the CT scan acquisition protocol among study sites before study enrollment. For this run-in phase, subjects underwent CTA and calcium scoring but not SPECT or conventional angiography. All scan acquisitions for this run-in phase were performed between September 2009 and January 2010.

Image acquisition

All examinations were performed using a 320-detector row CT scanner (Aquilion® ONE, Toshiba Medical Systems). All subjects fasted for at least 4 h prior to scanning and had no caffeine intake for 12 h. Subjects were hydrated prior to CT scanning using intravenous application of normal saline (250-500 mL). If subjects' heart rate (HR) was greater than 65 beats per min (bpm) and body mass index (BMI) was less than 30 kg/m², 75 mg of metoprolol was given orally. If BMI was 30 kg/m² or over, 150 mg metoprolol was given. If HR remained greater than 60 bpm despite oral beta blockade, 5.0 mg intravenous metoprolol was applied every 5 min for a maximum dose of 15 mg to achieve a HR less than 60 bpm. Sublingual nitroglycerin or isosorbide dinitrate (400 mcg spray or 0.4 mg tablet) was administered before scanning if the subject's systolic blood pressure was greater than 110 mmHg. Calcium scanning was performed at 120 kV and 140 mA with a gantry rotation of 0.35 s, collimation of 3 mm, and scan range of 128-160 mm. For CTA, subjects underwent scanning using a collimation of 0.5 mm and gantry rotation of 0.35 second. If HR was less than 66 bpm at the time of imaging, prospective scan triggering was performed at 70-80% of one R-R interval with X-ray exposure time ranging from 0.35 to 0.42 s. For subjects with HR over 65 bpm despite beta blockade, a 2-heartbeat image acquisition protocol was applied with prospective scan triggering and 40-80% exposure window. If BMI was over 30 kg/m², a one-beat scan with exposure window of 40-80% was performed even if the HR was over 65 bpm to keep radiation doses low. Peak

Table 1. Exposure charts.

BMI, kg/m ²	Tube current, mA			
	Men		Women	
	1-beat scan	2-beat scan	1-beat scan	2-beat scan
<19.9	350	350	300	300
20-24.9	400	400	370	340
25-29.9	450	440	400	340
30-34.9	520	*	450	*
35-39.9	550	*	460	*
>40	570	*	460	*

BMI, body mass index. *Forced to 1-beat scan with 40-80% of one R-R interval.

tube voltage was set at 120 kV for all subjects but tube current was adjusted between 300-570 mA depending on BMI, HR and gender (Table 1). By protocol, peak tube voltage could not be altered because of concerns of affecting the myocardial perfusion analysis for the CORE320 study. Iopamidol (Isovue 370, Bracco Diagnostics) was injected using an 18- or 20-gauge i.v. line with image acquisition triggered automatically at 300 HU in the descending aorta (bolus tracking method). Contrast medium was injected using a dual-head power injector. The flow of the contrast agent was adjusted according to each subject's weight (50 mL: 4 mL/s for <60 kg; 60 mL: 4.5 mL/s for 60-69.9 kg; 60 mL: 5 mL/s for 70-99.9 kg, 70 mL; 5 mL/s for >100 kg). At least 3 clinical CT scans were performed at each participating site. A copy of the raw data was sent to the core lab at the Johns Hopkins University.

Computed tomography angiography image analysis

The PhaseXact® scanner software (Toshiba Medical Systems) automatically determined the cardiac phase with least cardiac motion for CTA image reconstruction. Raw image data sets were reconstructed at a 0.5-mm slice thickness with a 0.25 mm overlap. Images were reconstructed using both a standard (FC43) and a sharp (FC05) convolution kernel. A temporal window of plus (+) and minus (-) 20 ms was used to permit a better assessment of proximal and distal coronary arteries in case of minor variations in movement. The reconstructed CTA images were transferred to a workstation with commercial cardiac CT software package (Vitrea FX version 3.0, Vital® Images) for image analysis. All studies were evaluated by a single blinded observer with a second investigator providing blinded reads for reader variability assessment. Total coronary calcium burden was estimated using the Agatston method, carefully avoiding stents and extra-coronary calcium. Coronary arterial segments were labeled using a modified 29-coronary arterial seg-

ment model resulting in 19 segments analyzed per patient.²

Contrast to noise ratio

Contrast to noise ratio (CNR) was assessed for the aorta, left main coronary artery (LM) and proximal and mid segments of the left anterior descending coronary artery (LAD), left circumflex coronary artery (LCx) and right coronary artery (RCA). Coronary vessel contrast was defined as the difference in the mean density (in Hounsfield units; HU) between the contrasts enhanced vessel lumen and the mean density in the adjacent perivascular fat. Image noise was defined as standard deviation of attenuation value of region of interest (ROI) in ascending aortic lumen. All measurements were obtained using axial image projections.

Image quality assessment

Image quality was qualitatively assessed on a study level as well as on a segment level using an ordinal 4-point scale (Figure 1): i) Optimal, *i.e.* absence of any image artifacts; ii) Adequate, *i.e.* minor artifacts may be present with overall acceptable noise levels; iii) Limited, *i.e.* major artifacts may be present with overall substantial noise levels resulting in low confidence assessment; iv) non evaluable, *i.e.* image quality does not allow image interpretation with any confidence.

Radiation dose assessment

The dose-length product (DLP) is an indicator of the integrated radiation dose of an entire CT examination defined as: DLP (mGy × cm) = CTDI (computed tomography dose index) × scan length. Effective radiation dose in mSv for the *entire* CT examination (scout images, calcium score, bolus-tracking, CT angiography) was estimated by multiplying DLP with coefficient k (0.014 for chest examination).¹⁵

Statistical analysis

Continuous variables are presented as

mean±SD and discrete variables as frequencies and percentages. The χ^2 test was used for the comparison of categorical variables. The Kruskal-Wallis test was used to test for differences among three BMI categories due to small sample size within each category and not normal data distribution. *Post hoc* pairwise analysis was performed using the Mann-Whitney test and significant differences were tested using Bonferroni's correction. Mann-Whitney test was performed to compare the 1-heartbeat scan and the 2-heartbeat scan acquisition protocol. Simple linear regression analysis was performed on image noise to BMI or tube current, and on contrast to BMI or contrast dose or tube current. Multivariable logistical regression analysis was performed to investigate predictors of optimal image quality using a stepwise method. Interobserver variability for categorical image quality assessment was evaluated using kappa statistics and for continuous data (contrast noise ratio measurements) using Bland-Altman analysis (n=65 for both). P<0.05 was considered statistically significant. All data were analyzed using SPSS software version 17.0 (SPSS Inc.).

Results

The study population consisted of 41 men and 24 women; mean age 58.8±12.3 years. All subjects were in sinus rhythm and were clinically stable. Subjects were on average mildly overweight (mean BMI 26.6±5.5 kg/m²). Average heart rate at image acquisition was 55.0±7.3 bpm. Median Agatston calcium score was 27.0 (interquartile range 1-330). Only 4 of 65 (6.2%) studies required a 2-beat scan acquisition for inadequate HR control. Table 2 summarizes results for subjects stratified according to BMI. Twenty-seven subjects were of normal weight (BMI<25 kg/m²), 25 were overweight (BMI 25-29.9 kg/m²), and 13 were obese (BMI ≥ 30 kg/m²). No significant differences were observed in age, HR or Agatston calcium score among the three groups. Contrast dose was significantly greater in the obese group than other groups (normal 51.9±8.3 mL; overweight 54.9±3.8 mL; obese 61.9±4.9 mL; P<0.001). After exclusion of 2-beat scan acquisitions (which were unevenly distributed among groups) estimated radiation doses were significantly greater in obese than the normal weight or overweight groups (normal 4.6±0.3 mSv; overweight, 4.7±0.3 mSv; obese, 5.3±0.4 mSv; P<0.001).

Image quality

Four subjects had a CT study of only limited image quality. All of these 4 had 1-beat

scan acquisition. Of these 4, 2 had severe motion artifacts in the RCA. One of these four studies with limited image quality had poorly controlled HR and received a single beat scan even though a HR of 69 bpm called for a 2-beat scan acquisition (protocol deviation). Two of these 4 subjects with limited image quality were morbidly obese (41.3 and 47.0 kg/m²). Overall, 61 of 65 (93.8%) had diagnostic image quality on a subject level. Diagnostic image quality was found in 96.0% on a coronary segment level (437 of 455). There were no studies of limited image quality among those 4 scans using 2-beat scan acquisition. Subjects with normal BMI had significantly better image quality than over-

weight and obese subjects (optimal image quality: normal 100.0%; overweight 56.0%; obese 30.8%; P<0.001). Only 4 of 13 (30.8%) obese subjects had excellent image quality despite similar HR and Agatston calcium scores. The obese group had significantly lower image quality in the LM, proximal LCx, mid LCx than subjects with normal weight (obese 1.5±1.0, 1.4±0.8, 1.5±0.8; normal weight 1.0±1.0, 1.0±1.0, 1.0±1.0; all P<0.05). There was no significant difference in image qualities of proximal LAD, mid LAD, proximal RCA, and mid RCA among the three groups (all P≥0.05). Table 3 shows the result for image noise, contrast, and CNR according to subjects' BMI. Image noise was significantly

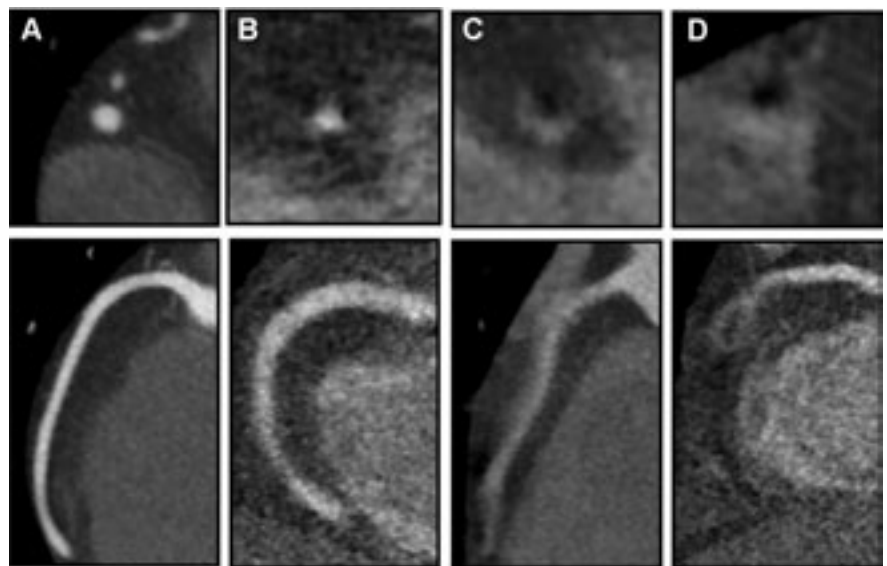


Figure 1. Qualitative image quality assessment. Examples of images of different image quality. Image quality was subjectively assessed on a study and segment level using a 4-point scale: A) optimal, absence of any image artifacts; B) adequate, minor artifacts may be present with overall acceptable noise levels; C) limited, major artifacts may be present with overall substantial noise levels resulting in low confidence assessment; D) non-evaluable, image quality does not allow image interpretation with any confidence.

Table 2. Summary of subjects' characteristics for subgroups.

	Normal weight n=27	Overweight n=25	Obese n=13	P
Age, years	59.8 (11.9)	63.9 (14.2)	55.1 (9.8)	0.062
Heart rate, bpm	55.4 (9.5)	54.2 (5.3)	57.5 (5.0)	0.172
BMI, kg/m ²	22.4 (2.0)	27.5 (1.4)*	34.3 (5.0)*°	<0.001
Contrast dose, mL	51.9 (8.3)	54.9 (3.8)*	61.9 (4.9)*°	<0.001
Scan range, mm	140.2 (9.3)	138.0 (9.3)	142.1 (8.6)	0.448
Tube current, mA	386.0 (49.3)	424.1 (25.5)*	518.9 (35.0)*°	<0.001
Radiation dose (all), ^a mSv	5.0 (1.1)	4.8 (0.8)	5.3 (0.4)°	<0.001
Agatston calcium score	351.0 (624.2)	408.8 (717.4)	312.0 (777.8)	0.921
2-beat scan, n	3	1	0	0.333
Radiation dose (single beat only), ^b mSv	4.6 (0.3)	4.7(0.3)	5.3 (0.4)*°	<0.001

BMI, body mass index; bpm, beats per minute. Data are given as mean (SD). P<0.05 was significant. *Significant difference compared to normal weight; °Significant difference compared to overweight. °All subjects; °2-beat scan acquisitions (n=4) were excluded from this analysis.

greater in the obese and overweight groups than in the normal weight group ($P<0.001$). Image contrast for the aorta, LM, proximal LAD, mid LAD, proximal LCx, proximal RCA, and mid RCA were all significantly lower in the obese group compared to subjects with normal weight (all $P<0.05$). The CNR of aorta, LM, proximal LAD, mid LAD, proximal LCx, mid LCx, proximal RCA, and mid RCA were significantly lower in the overweight and obese groups compared to the normal weight group (all $P<0.001$). When only considering 2-beat scan acquisitions ($n=4$), the studies had median (IQR) image quality of 1 (1-1.75), image noise of 17.5 (14.4-24.3), contrast (proximal LAD) of 445.7 (398.9-535.9), CNR (proximal LAD) of 25.4 (19.3-32.7). There were no significant differences between a 1-beat and 2-beat scan acquisition (all $P>0.05$) except for radiation dose (1-beat scan; 4.8 mSv (4.6-4.8), 2-beat scan; 7.7 mSv (7.1-9.1), $P<0.001$).

Impact of subject body mass index and scan acquisition settings on image noise

Figure 2 shows the correlation between BMI and image noise. There was a statistically significant positive correlation between image noise and BMI ($r = 0.769$, $P<0.001$) and mA ($r=0.519$, $P<0.001$). Image contrast (proximal LAD) negatively correlated with BMI ($r=-0.442$, $P<0.001$), contrast dose ($r=-0.333$, $P<0.007$) and mA ($r=-0.288$, $P<0.020$). CNR correlated negatively with BMI ($r=-0.508$, $P<0.001$), contrast dose ($r = -0.465$,

$P<0.001$) and mA ($r=-0.661$, $P<0.001$). In univariate analysis, BMI, contrast dose and tube current were significantly associated with image quality. In multivariable analysis, BMI was the strongest predictor of optimal image quality *vs* adequate to limited quality after

holding age, gender, HR, Agatston calcium score and scan range (odds ratio=1.457, $P=0.005$). Figure 3 shows an example of two cross-sectional images acquired by contrast enhanced 320-row CT to demonstrate the influence of subjects' BMI on image quality.

Table 3. Image noise, contrast, and contrast-to-noise ratios for subgroups.

	Normal weight n=27	Overweight n=25	Obese n=13	P
Image noise, HU	19.0 (4.7)	28.3 (8.5)*	37.0 (15.0)*	<0.001
Image contrast				
Aorta, HU	513 (68)	489 (67)	454 (79)*	0.042
LM, HU	471 (79)	449 (69)	389 (49)†°	0.003
Proximal LAD, HU	470 (75)	431 (79)	379 (80)*	0.009
Mid LAD, HU	438 (89)	399 (62)	372 (86)*	0.041
Proximal LCx, HU	449 (82)	403 (79)	361 (73)*	0.005
Mid LCx, HU	396 (90)	367 (83)	331 (88)	0.093
Proximal RCA, HU	453 (114)	432 (66)	373 (79)*	0.011
Mid RCA, HU	413 (84)	376 (62)	325 (45)*°	0.001
Contrast to noise ratio				
Aorta	28.7 (8.7)	19.2 (7.7)*	14.4 (5.9)*	<0.001
LMT	26.4 (8.3)	17.6 (7.1)*	12.3 (5.1)*	<0.001
Proximal LAD	26.5 (8.8)	16.7 (6.3)*	12.0 (5.1)*	<0.001
Mid LAD	24.5 (7.8)	15.3 (5.1)*	11.7 (5.2)*	<0.001
Proximal LCx	24.8 (6.7)	15.6 (5.9)*	11.6 (6.1)*	<0.001
Mid LCx	21.5 (5.3)	14.5 (6.4)*	10.9 (6.1)*	<0.001
Proximal RCA	24.6 (8.7)	16.8 (6.2)*	12.0 (6.2)*	<0.001
Mid RCA	22.8 (6.5)	14.7 (6.1)*	10.2 (4.2)*°	<0.001

Data are expressed as mean (SD). $P<0.05$ was significant. HU, Hounsfield units; LAD, left anterior descending coronary artery; LCx, left circumflex coronary artery; LM, left main coronary artery; RCA, right coronary artery. *Significant difference *vs* normal. °Significant difference compared to overweight.

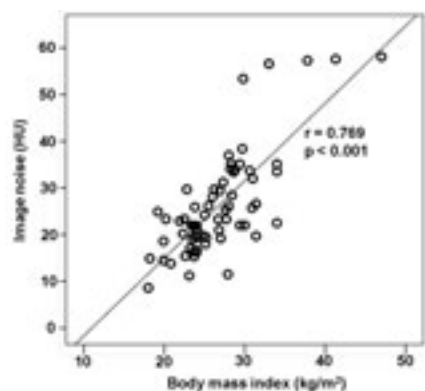


Figure 2. Relationship between body mass index and image noise. The result of regression analysis is shown for image noise and body mass index (BMI). There was a statistically significant positive correlation of image noise with BMI ($r=0.769$, $P<0.001$). Image noise was defined as standard deviation of attenuation value of region of interests in ascending aortic lumen using axial image projections.

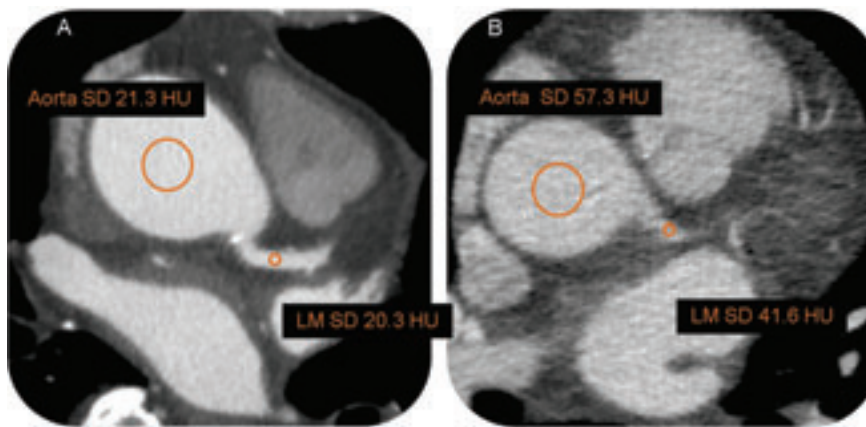


Figure 3. Case examples. Examples are shown of two cross-sectional images acquired by contrast enhanced 320-row computed tomography (CT) coronary angiography to demonstrate the influence of subject body mass index (BMI) on image quality. Image noise in case B (BMI 37.8 kg/m²) was substantially greater than in case A (BMI 19.9 kg/m²), despite higher tube current settings in case B. Case A: a 76-year old man with a BMI of 19.9 kg/m² (normal weight group), heart rate (HR) of 54 beats per minutes (bpm), tube current of 400mA, scan range of 140 mm, radiation dose of 4.8 mSv and image noise in the aorta of 14.5 Hounsfield units (HU) *vs* left main coronary artery (LM) of 21.2 HU. Case B: a 70-year old woman with a BMI of 37.8 kg/m² (obese group), HR of 65 bpm, tube current of 460 mA, scan range of 140 mm, radiation dose of 4.8 mSv, and image noise in the aorta 58.1 of HU *vs* LM of 47.4 HU.

Reader variability

Measurement of interobserver variability using the kappa statistic yielded 0.84 for image quality. There was a good correlation between observer 1 and 2 for contrast noise ratio (CNR) ($r = 0.68$, $P < 0.001$). The Bland-Altman plot for the same assessment revealed a high concordance (average difference 0.26).

Discussion

Overall, the CORE320 CTA scan acquisition protocol resulted in studies with a good balance between image quality and radiation dose to the patient. Most scans required only a single beat scan acquisition. Subject BMI was the strongest factor influencing image quality.

Compared with the 64-slice CT technology used in the CorE-64 study, image quality in this CORE320 run-in phase was better at substantially lower radiation doses.^{2,16} Dewey *et al.* reported high diagnostic accuracy for detecting coronary arterial stenoses using 320-row CTA, with significantly lower radiation doses (4.2 vs 8.5 mSv) compared to conventional coronary angiography.⁶ The advantage of 320-row CT scanning is a short scan acquisition time due to wide z-axis coverage enabling the acquisition of a full cardiac CT dataset within a single heartbeat.⁶⁻⁸ Accordingly, prospective scan triggering is not associated with step artifacts or unequal contrast opacification as may be seen with small coverage scanners.¹⁷ Furthermore, there are fewer contrast requirements.¹⁰

Impact of subjects' characteristics and scan acquisition on image quality

Our data confirmed that BMI strongly correlates with image noise ($r = 0.769$). Image quality in obese subjects was significantly reduced compared to normal weight subjects. BMI is a known major factor affecting image quality in coronary CT angiography.^{16,18,19} While 77% of obese patients in our study had diagnostic image quality with the CORE320 protocol, subjects with morbid obesity had limited image quality. A likely explanation is the tube voltage restriction by the CORE320 protocol implemented to avoid affecting myocardial perfusion analysis. As anticipated, increasing tube current reduced image noise in our study. However, increases in tube current were kept to a minimum to avoid high radiation doses to the subject.

Heart rate control considerations for 320-row computed tomography

Our study revealed that motion artifacts are

not infrequent with 320-row CTA, although diagnostic image quality was maintained in most cases. One of the limitations of current generation 320-slice CT is its only moderate temporal resolution when using single beat scan acquisition (approx. 175 ms).²⁰ Though gantry rotation speed has been increased compared to 64-slice scanners by the same vendor, a low HR (<65 bpm) is still required to obtain high quality coronary images using single beat scan acquisition. Greater temporal resolution is available with the 320-slice scanner by using multi-segmental image reconstructions over two or more heartbeats (up to 5) but radiation dose essentially doubles with each additional beat acquisition. In this study, we found that 2-beat scan acquisition was rarely necessary if a good beta blocker protocol was enforced. For the 4 studies with 2-beat scan acquisition, the HR range was 58-81 bpm and yet images remained free of significant motion artifacts. Therefore, our data suggest single beat acquisition can be performed with diagnostic image quality unless HR during breath hold exceeds 65 bpm. For greater heart rates, 2-beat acquisition may be required to avoid significant motion artifacts but a 3- or more beat scan acquisition may rarely be necessary.

Study limitations

Our patient population was relatively small, limiting the interpretation of results in patients with higher heart rates. Our protocol did not include a wide exposure window as alternative to a 2-beat scan acquisition. A wider exposure window may be an adequate strategy to limit radiation dose increase while maintaining diagnostic image quality.⁹ Lastly, image quality but not diagnostic accuracy was used to assess the performance of our image acquisition protocol in this study, limiting the assessment of the clinical impact of our findings.

Conclusions

The CORE320 CT image acquisition protocol achieved a good balance between image quality and radiation dose to patients and may serve as a guide to clinical scan acquisition using a 320-row system. Using stringent beta blockade, 2-beat image acquisition was rarely necessary, keeping radiation doses low. However, image quality in obese subjects was significantly reduced compared to normal weight subjects which may, at least partly, be because of the tube voltage restrictions mandated by the study protocol.

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