Image Quality in Reduced-Dose Coronary CT Angiography

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Rationale and Objectives: Concerns for patient's risk of radiation-induced cancer have increased demand for reduced-dose coronary computed tomography angiography (CCTA). Previous comparisons of full and reduced-dose CCTA were not conclusive, because results were compared in different groups of patients. Presented here are results in patients examined by a widely used full dose CCTA protocol and a new low-dose alternative.

Materials and Methods: Standard full-dose and low-dose CCTA with tube voltages of 120/100 kV were applied on 70 patients with intermediate probability of coronary artery disease (CAD). Both protocols used prospective electrocardiogram-gated acquisition on a 320-detector row CT scanner, whereas at low-dose CCTA the phase window was increased from 10% to 75% of R-R interval.

Results: Despite a mean dose reduction of 80%, from 4.9 $\pm$ 0.98 to 0.98 $\pm$ 0.24 mSv, visual image quality was not significantly affected at the low-dose protocol. Contrast level, image noise, and CNR for both protocols were similar in the majority of coronary segments. CNR for standard and low-dose protocol were 23.7 $\pm$ 17.1 and 23.2 $\pm$ 26.8, P = NS. Correlation between visual image quality and heart rate variability was strong at low dose: $r = -0.58$, $P = .01$, and absent at full dose: $r = -0.07$, $P = .77$.

Conclusion: Image quality of blood vasculature is generally not affected by 80% CCTA dose reduction applied to standard prospective electrocardiogram-gated acquisition. The performance at the low-dose protocol owes to the increased phase window, enhancing image quality at the cost of sensitivity to heart rate variability as compared with standard CCTA.

Key Words: Angiography; coronary arteries; contrast-to-noise ratio; radiation dose; 320-row computed tomography.

During the past decade, there has been a dramatic increase in the number of computed tomography (CT) examinations performed worldwide. The principal concern for any patient undergoing a diagnostic CT examination is the risk of developing a radiation-induced cancer, which may be fatal or nonfatal (1). Reducing the radiation dose while maintaining highest image quality possible has therefore become an important research topic. Furthermore, with existing helical CT systems, the z-coverage is limited to maximum 4 cm data acquisition in a single rotation. Any future use of additional rotations to cover the whole heart by the helical acquisition method will increase the radiation dose, the amount of which depends on the pitch.

Low-dose coronary CT angiography (CCTA) has recently been used in several studies (2–5). However, direct comparison in terms of image quality assessment between low-dose and standard full-dose protocols on the same group of patients is still lacking. The purpose of this study is to present a quantitative comparison of image quality for two scanning protocols applied in the same patient examination: full-dose (standard CCTA with tube voltage 120 kV) and a new low-dose protocol with tube voltage 100kV. Both protocols use prospective electrocardiogram (ECG)-gated acquisition on a 320-detector row CT scanner. This way, acquisition of the whole heart is achieved during a single heart beat in nonhelical scan acquisition. At the resulting exposure and scan time of just 0.35 seconds, the radiation dose is considerably reduced compared with helical data acquisition. Prospective ECG-gating also presents an opportunity for widening cardiac phase window still within one heart beat, a technique called padding (Fig 1). This technique, which allows for the reconstruction of more cardiac phases within a single heart beat, still without pitch value (pitch = 0), has been implemented in the new low-dose protocol by increasing the phase window from the standard setting of 10% to 75% of R-R interval.

MATERIALS AND METHODS

Patient Population

Between June and September 2009 a total of 70 patients with intermediate probability of coronary artery disease (CAD) according to the Coronary Artery Surgery Study Scale (6) was enrolled at First Moscow State Medical University. All

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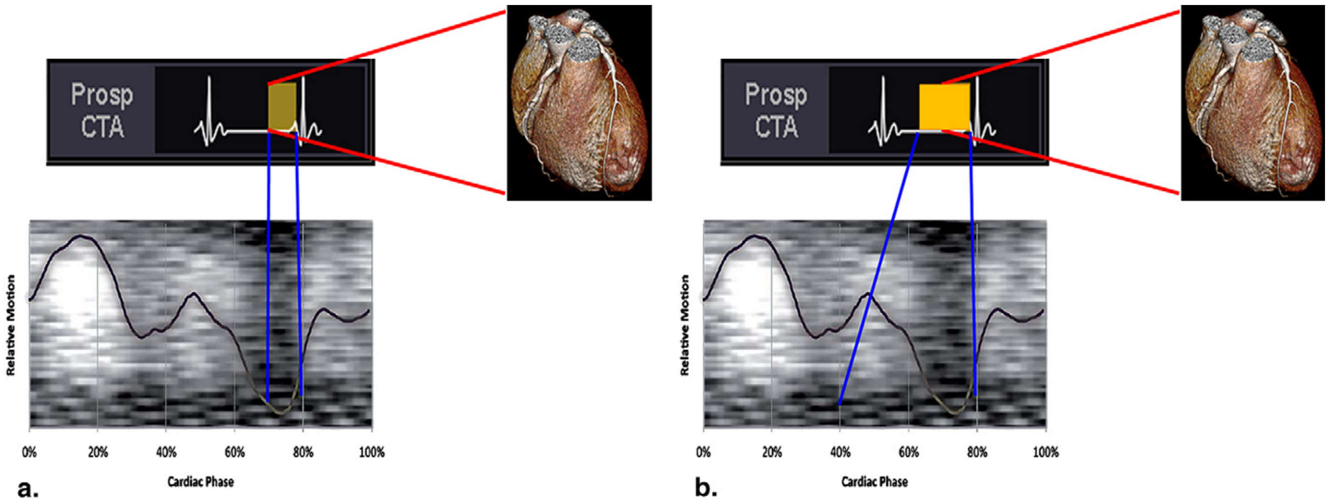


Figure 1. **(a)** Prospective electrocardiogram-gated acquisition method aiming at 70%–80% of R-R interval and **(b)** padding of for example 40%–80% of R-R interval. The height of the pulse represents the *z*-coverage.

patients were referred for the exclusion of CAD. Patients were eligible for the study if they had sinus rhythm and body mass index (BMI) less than 30 kg/m^2. The latter criterion was imposed in view of minimum image quality required to allow for quantitative assessment of diagnostic performance. Patients with contraindications to contrast-enhancement multidetector CT (impaired renal function with serum creatinine level >1.2 mg/dL or allergic reactions to iodinated contrast agents) were not examined. Further exclusion criteria were pregnancy and breastfeeding and prior coronary artery bypass graft or stent. The study protocol had institutional review board approval, and all patients participated with written informed consent. Mean age was 57.3 ± 12.7 years (range, 37–76 years, median 57 years). Fifty-one patients (73%) were males, 19 patients (27%) were females, mean weight was 73.4 ± 10.5 kg (range, 52–95 kg, median 75 kg), and mean height was 167.4 ± 9.1 cm (range, 150–182 cm, median 170 cm). Mean BMI was 25.8 ± 2.4 kg/m^2, range 21–30 kg/m^2, median 25 kg/m2 (nonobese patients). Minimum and maximum heart rate was determined by an automated procedure in the scanner during breathing exercises performed during 12 seconds before each study. Accordingly, heart rate variability was calculated on the basis of these indices. Heart rate thus calculated during breath hold after submaximal inspiration, ranged from 49 to 65 beats/minute (ie, 56.4 ± 6.1 beats/minute) for full-dose protocol and similar (55.9 ± 6.9 beats/minute) for low dose protocol.

Scan Protocol

All examinations were performed on a 320-detector row CT scanner (Toshiba Aquilion ONE, Toshiba Medical Systems, Otawara, Japan). All patients with a resting heart rate >65 beats/minute received propranolol 20–40 mg or atenolol 25–50 mg per patient before scanning.

Scout imaging was followed by a precontrast study for calcium scoring quantification and for precise determination of the scan range, which may vary between 10 and 16 cm. Volume scan mode (pitch = 0, without table movement) was used. The scan range was planned between the carina and cardiac apex (up to 16 cm). The rotation time was set to 350 ms. The field of view varied between 240 and 320 mm depending on the patient size, and slice thickness was 0.5 mm. Prospective ECG synchronization was used. The total scan and exposure time were therefore 350 ms. After precontrast scanning and precise scan range determination, CCTAs according to two different protocols were acquired sequentially over 30 minutes.

For the standard full-dose protocol, tube voltage was set to 120 kV, tube current was varied with BMI (between 400 mA for BMI 21 and 500 mA at BMI 30; mean, 440 mA) and width of the phase window 10% (range, 70%–80% of R-R interval). For the second protocol, tube voltage was reduced to 100 kV, tube current varied between 200 mA for BMI = 21 and 570 mA for BMI = 30 (mean, 370 mA) and the width of the phase window was fixed at 75% of R-R interval. Intravenous injection of 50 mL (or 60 ml if patient's weight was more than 90 kg) contrast medium (Omnipaque, 350 mgI/mL or Visipaque, 320 mgI/mL) with an injection rate of 5 mL/second followed by 20 mL normal saline was used for each protocol.

The datasets for both protocols were reconstructed with a smooth soft-tissue convolution filter. The density measurements (mean attenuation of the contrast medium, image noise, contrast-to-noise ratio were performed in ascending aorta, left ventricle, and 10 segments of coronary arteries: left medial, proximal, middle, and distal segments of left anterior descending (LAD) artery, circumflex (Cx), and right coronary artery (RCA) (segments 1–8, 11, 13, and 15 according to American Heart Association) (7). Mean attenuation of the contrast medium was measured by 1.02 mm^2 circular region of interest (ROI) in each segment. Image noise was defined as the standard deviation within the ROI and the contrast-to-noise ratio (CNR) was calculated by division of the difference between the vascular density and the perivascular density by the image noise: CNR = (vascular density-perivascular density)/image noise.

Visual Image Quality Assessment

Three radiologists with more than 2 years of relevant experience assessed diagnostic image quality on per-patient basis using a 4-point scale ranging from 1 to 4:

1: nondiagnostic images

2: adequate (moderate artifacts, but still diagnostic)

3: good (minor artifacts with good diagnostic quality)

4: excellent quality, without any artifacts.

Assessment was blind meaning that image quality was assessed on a workstation on randomized datasets stripped from information regarding the measurement protocol. Hemodynamically significant stenosis was defined as >50% of luminal diameter.

Evaluation of the Effective Radiation Dose

The volume CT dose index ($CTDI_{vol}$) and the dose-length product (DLP) as provided by the scanner system were recorded. Patient radiation dose was calculated by multiplying DLP by a conversion factor of 0.017 $mSv{\star}mGy^{-1}{\star}cm^{-1}$ for the chest according to a method proposed by the European working group for Guidelines on Quality Criteria in CT (8).

All statistical analyses were performed with statistical packages (SPSS for Windows, SPSS, Chicago, IL; MedCalc for Windows, MedCalc Software, Belgium). Quantitative variables are expressed as mean ± standard deviation. Comparisons of the paired results of the two protocols were analyzed using the paired *t*-test. Determining the correlation was performed by using Pearson's correlation analysis. Differences were considered significant when the *P* value was less than .05.

RESULTS

At the new low-dose protocol, using 100 kV instead of 120 kV and an increased phase window, the standard CCTA radiation dose was reduced by an average of 80%. DLP for standard protocol was 289.9 ± 57.9 mGy⋆cm (232–456 mGy⋆cm, median 275 mGy⋆cm); therefore, mean patient dose was 4.9 ± 0.98 mSv (3.9–7.75 mSv, median 4.67 mSv). For the low-dose protocol, mean DLP values were calculated of 35.0, 41.5, 57.7, 57.3, 61.2, 61.1, 63.7, and 76.0 mGy⋆cm for BMIs of 21, 23, 24, 25, 26, 27, 28, and 29, respectively (r = 0.64; P < .001). At the low-dose protocol, median DLP was 55 mGy⋆cm (57.6 ± 14.1 mGy⋆cm) and therefore mean patient dose was 80% lower: 0.98 ± 0.24 mSv (0.6–1.4 mSv, median 0.93 mSv) (ie, for up to 16 cm *z*-coverage; collimation 320 × 0.5 mm).

Nevertheless, in the visual evaluation of hemodynamically significant stenoses, there were no differences between standard and low-dose protocols. Mean calcium score was 243.5 ± 400.8 (range, 0–1235; median 46). Evaluation of all patient data restricted to either protocol indicated that in 41% of patients (29 of 70), no coronary artery lesion was present, 37% had minimal changes and nonsignificant stenotic lesions (<50%), and 21% of patients (15 of 70) had significant stenoses (>50%). Invasive coronary angiography was performed after CT in 16 patients within 30 days. Results for coronary stenoses were thus confirmed in all 15 patients of the latter category. After evaluation of the severity of the epicardial stenoses on CCTA images, no significant differences between the protocols were observed.

Quantitative Assessment of Diagnostic Performance

Both protocols were successfully performed in all 70 patients. In total, 700 coronary artery segments were evaluated for each protocol. In the standard protocol, measurements were impossible in 16 segments (ie, 2.2%; 4 in middle LAD from extensive coronary calcification; 4 in distal LAD, 4 in middle Cx, and 4 in distal Cx; all from very small artery diameter, less than 1 mm). Low-dose protocol evaluation was not possible in 20 segments or 2.8% (4 in middle LAD from extensive coronary calcification; 4 in distal LAD, 4 in middle Cx, and 8 in distal Cx; all from very small artery diameter, less than 1 mm).

Mean attenuation of the contrast medium, mean noise, and CNR within the coronary arteries, left ventricle and aorta are presented in Table 1. In the low-dose protocol, CNR is significantly reduced in aorta, left ventricle, and in middle segments RCA. Mean attenuation value is reduced in proximal and middle segments RCA as compared with standard protocol. There was no statistical difference between mean contrast level, image noise, and SNR for both protocols in other coronary segments. Moreover, there was no statistical difference between CNR in all assessable coronary segments for both protocols: mean CNR for full-dose protocol was 23.7 ± 17.1 (median, 18.8) and for low-dose protocol 23.2 ± 26.8 (median, 17.7), P = NS. CNR in all coronary segments collectively showed weak but highly significant inverse correlation to BMI: $r = -0.15$, P = .0001. This correlation was similar for standard protocol ($r = -0.17$, P = .0001) and for low-dose protocol ($r = -0.12$, P = .0007), P = NS. Vessel density and CNR were significantly lower and image noise significantly higher in proximal segments as compared with distal segments for both protocols (Fig 2).

Diagnostic Image Quality: Visual Assessment

Mean image quality scoring was 3.32 ± 0.7 for standard protocol and 3.29 ± 0.19 for low-dose protocol (P = NS) (Fig 3). Weakly correlated were image quality and BMI ($r = -0.35$, P = .03) for both protocols. With use of the two CCTA protocols in the same patient, increasing BMI therefore did not significantly affect image quality. Additionally, we found a correlation between visually assessed image quality and vessel density to a different degree on per-segment basis, stronger in distal segments. For left main, correlation coefficient was r = 0.35, P = .03; for LAD in proximal segments

TABLE 1. Quantitative Analysis Results of CCTA Image Quality Parameters in Various Regions Measured After Contrast Administration

Region	Standard Protocol Attenuation (HU) Image Noise (HU) CNR	Low-dose Protocol Attenuation (HU) Image Noise (HU) CNR	*P* Value
Ascending aorta	408.7 ± 90.4	388.3 ± 117.9	NS
	11.2 ± 6.7	12.7 ± 3.7	NS
	62.4 ± 68.7	34.9 ± 21.4	.002
Left ventricle	374.7 ± 95.5	360.2 ± 96.3	NS
	14.9 ± 8.5	16.0 ± 6.7	NS
	36.0 ± 26.2	26.6 ± 14.8	.01
Coronary arteries: left main	352.7 ± 81.1	366.9 ± 94.5	NS
	16.0 ± 10.1	14.4 ± 6.1	NS
	28.9 ± 15.1	30.3 ± 16.1	NS
Coronary arteries: LAD proximal	319.9 ± 91.7	330.6 ± 89.7	NS
	20.4 ± 9.7	18.7 ± 6.5	NS
	19.4 ± 10.2	21.4 ± 8.7	NS
Coronary arteries: LAD middle	316.6 ± 66.7	325.3 ± 89.8	NS
	20.6 ± 10.7	18.6 ± 6.6	NS
	16.2 ± 10.7	19.6 ± 15.3	NS
Coronary arteries: LAD distal	242.7 ± 58.4	230.2 ± 58.9	NS
	25.5 ± 12.7	25.8 ± 8.7	NS
	11.3 ± 5.1	9.9 ± 4.3	NS
Coronary arteries: Cx proximal	299.4 ± 73.5	324.1 ± 102.2	NS
	18.3 ± 6.8	19.3 ± 9.7	NS
	19.2 ± 9.8	22.7 ± 17.3	NS
Coronary arteries: Cx middle	300.8 ± 68.9	308.9 ± 83.8	NS
	17.8 ± 8.2	19.0 ± 7.2	NS
	19.9 ± 9.1	18.6 ± 7.9	NS
Coronary arteries: Cx distal	238.0 ± 54.9	260.1 ± 83.1	NS
	24.0 ± 10.1	22.0 ± 6.8	NS
	14.2 ± 12.5	12.8 ± 4.7	NS
Coronary arteries: RCA proximal	345.0 ± 85.6	316.3 ± 67.4	.02
	15.0 ± 5.2	17.4 ± 8.7	NS
	27.0 ± 14.9	26.3 ± 25.0	NS
Coronary arteries: RCA middle	310.9 ± 74.6	270.7 ± 66.2	.001
	20.4 ± 8.8	23.1 ± 11.4	NS
	20.1 ± 13.9	14.1 ± 6.7	.001
Coronary arteries: RCA distal	268.4 ± 78.9	276.9 ± 74.8	NS
	24.4 ± 13.4	22.5 ± 11.6	NS
	14.7 ± 8.2	18.1 ± 16.4	NS

CCTA, coronary computed tomography angiography; Cx, circumflex; HU, Hounsfield units; LAD, left anterior descending artery; NS, not significant; RCA, right coronary artery.

$r = 0.46$, $P = .005$, in middle segments $r = 0.41$, $P = .01$, in distal segments $r = 0.55$, $P = .0009$. For Cx: in proximal segments $r = 0.3$, $P = .07$, in middle segments $r = 0.41$, $P = .01$, in distal segments $r = 0.27$, $P =$ NS. For RCA: in proximal segments $r = 0.33$, $P = .05$, in middle segments $r = 0.61$, $P = .0001$, in distal segments $r = 0.67$, $P = .0001$. Significant correlation between image quality and CNR only applied to distal segments LAD ($r = 0.34$, $P = .05$), Cx ($r = 0.54$, $P = .0008$), and RCA ($r = 0.33$, $P = .05$).

Heart Rate Variability versus Image Quality

During the examination heart rate was assessed, as described in the first paragraph of the Materials and Methods section. This allowed us to monitor the heart rate variability, a potential contributor to nonoptimal image quality. Mean heart rate variability was 2.66 ± 1.49 beats/minute (from 0 to 5 beats/minute, median 2 beats/minute), for standard protocol 2.79 ± 1.46 beats/minute and 2.53 ± 1.54 beats/minute for low-dose protocol. Although we found a strong inverse correlation between visual image quality and heart rate variability for the low-dose protocol: $r = -0.58$, $P = .01$, there was no such correlation for the standard protocol: $r = -0.07$, $P = .77$.

DISCUSSION

The main finding in this quantitative study using both standard and low-dose CTA protocol in all 70 patients included,

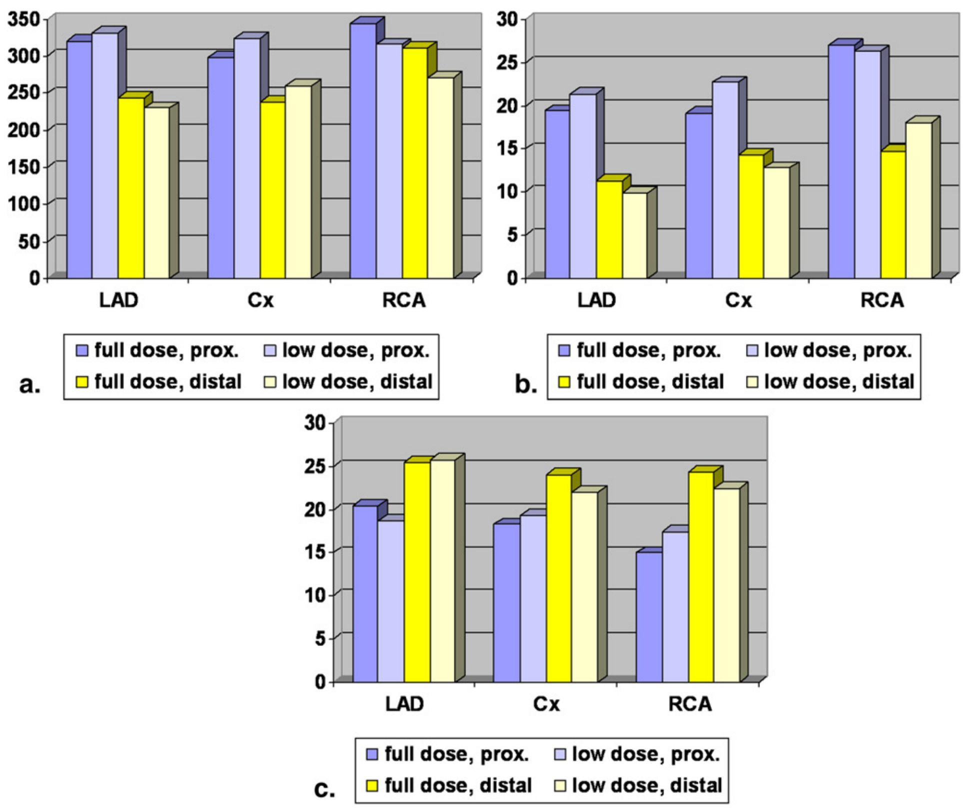
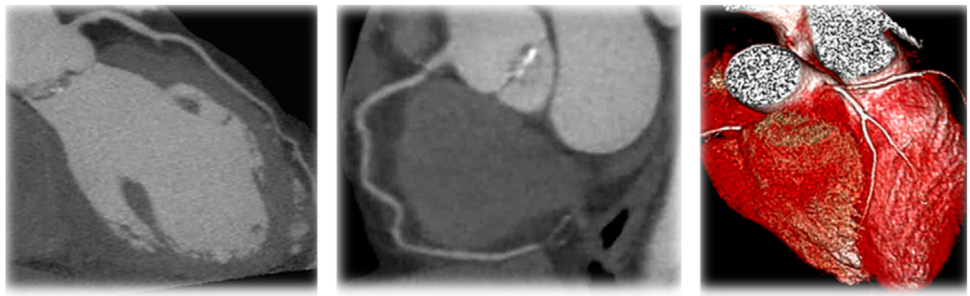


Figure 2. **(a)** Vessel density (in Hounsfield units [HU]) in proximal and distal segments for standard and low-dose coronary computed tomography angiography protocol. Low dose vs. full dose, all: $P < .0001$. **(b)** Contrast-to-noise ratio (CNR) in proximal and distal segments for standard and low-dose protocol. Low dose vs. full dose, all: $P < .0001$. **(c)** Image noise (in HU) in proximal and distal segments for standard and low-dose protocol. Low dose vs. full dose, all: $P < .0001$.

is that 80% radiation dose reduction can be achieved while maintaining image quality. Prospective ECG-gated 320-slice CCTA using a new low-dose protocol is compared with a widely used standard protocol in the same patient examination (one group of 70 patients). A 320-detector row CT allows for scanning of the whole heart during a single heart beat, with the possibility to pad when necessary. The *z*-coverage of up to 16 cm, and gantry rotation speed of 350 ms produce CCTA images with a temporal resolution of 175 ms across the *x*, *y*, and *z* directions. This uniform temporal resolution is very important when assessing the image quality as multiplanar reconstructions into views from various angles are necessary. Radiation dose is closely related to pitch value. A 320-detector row CT has the advantage that the dose is totally independent of the pitch as there is simply no table shift.

The demonstration here by visual assessment of low- and full-dose CCTA data from the *same* patient group of maintained image quality despite 80% dose reduction, fits with comparisons of *different* patient groups in respective 100/120 kV cohorts published elsewhere (9–12). Beside our assessment that comparisons of data from groups of different patients cannot be conclusive, another issue is that in those studies the dose reductions only varied between 40% and 54% as opposed to the 80% achieved here. One of those studies is hampered by the inclusion of lean patients (BMI <25) in the 100-kV cohort as opposed to BMI >25 in the 120-kV cohort (12). In the other three 100-kV vs. 120-kV CCTA comparisons in which the patients groups were matched, significant changes in vessel density (9–11) and also CNR decreases and noise increases (9,11) were observed in the coronary arteries. These findings contrast with the general pattern in our study, but might very well be due to comparisons between two groups of 82/88: 202/247 (multicenter) and 51/52 patients being less conclusive than those in 70 patients examined both ways in one examination (this study). Furthermore, in our case, the performance of the low-dose protocol was most probably enhanced by the increase in the phase window from 10% to 75% or R-R interval.

The quantitative assessments made in this study demonstrated that of 12 anatomic regions analyzed CNR loss only occurred in the ascending aorta, left ventricle, and in RCA middle. Considering that the ascending aorta and left ventricle still have very high CNR values at the low-dose protocol, we conclude that the result in only 1 of 12 anatomic regions (RCA middle) would indicate some loss of image quality. Illustrated in Figure 2 is that at both CCTA protocols, proximal and distal segments of the coronary arteries are equally well differentiated in terms of vessel density and CNR. Heart rate variability, a potential contributor to nonoptimal image quality, was similar for standard protocol (2.79 ± 1.46 beats/minute) and for low-dose protocol (2.53 ± 1.54 beats/minute). We observed strong inverse correlation between visual image quality and heart rate variability for the low-dose protocol only ($r = -0.58$, $P = .01$). This indicates that, despite the previously mentioned minimal loss of image quality at replacement of the standard protocol by the new low dose protocol, our ECG-gated CCTA results obtained with the latter protocol



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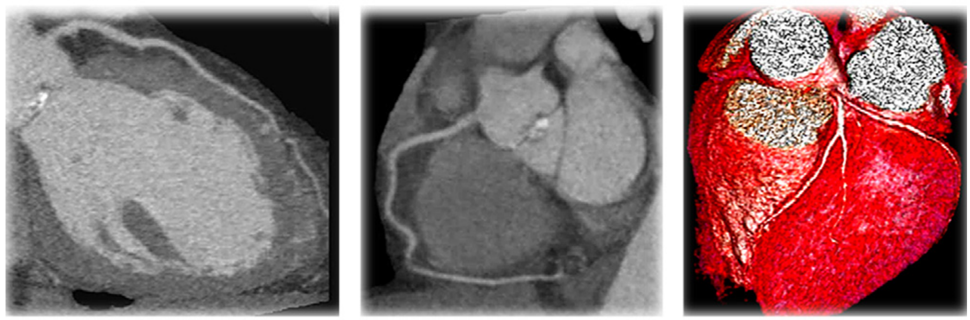


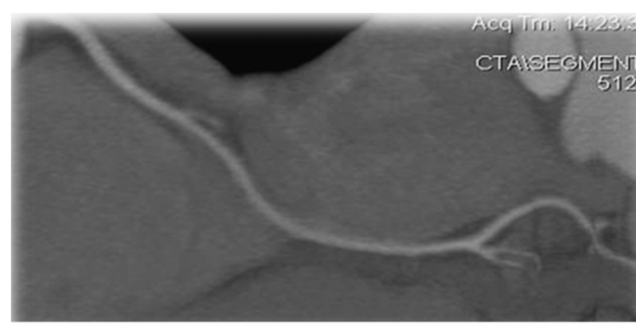
b.

Figure 3. A 320-detector coronary computed tomography angiography in a 37-year-old woman with nonspecific chest pain and dyspnea. Heart rate 63 beats/minute, body mass index 27. Extensive calcifications in aortal valve leaf are seen. **(a)** Standard protocol (4.1 mSv), **(b)** low-dose protocol (0.88 mSv).

are more sensitive to degradation of image quality by heart rate variations. This point is illustrated and explained in Figure 4. The degradation of image quality in relation to heart rate variability may thus reflect suboptimal results in a strictly fixed phase (75%) as opposed to a phase window varied over a range of 10% for optimal phase reconstruction.

The correlations between visual assessment and the quantitative assessments of image quality (vessel density, CNR) were essentially limited to the distal coronary arteries. This fits with the observation that the distal arteries had comparatively low vessel densities and CNR, making them relatively sensitive to noise and artefacts. In other words, in CCTA evaluation of the distal arteries image quality is more critical than in the evaluation of the more proximal and larger blood vessels.

Overweight (high BMI) is well-known to be a factor affecting image quality. One way to overcome the signal attenuation by the overlaying fat layers is to increase the tube current with increasing BMI. Although in the low-dose protocol this precaution was taken, in the coronary segments CNR still showed highly significant inverse correlation with BMI not different from that in the full-dose protocol. Also at visual evaluation the inverse correlation between image quality and BMI was significant. The worsening of image quality with increasing BMI is illustrated in Figure 5 (standard protocol).



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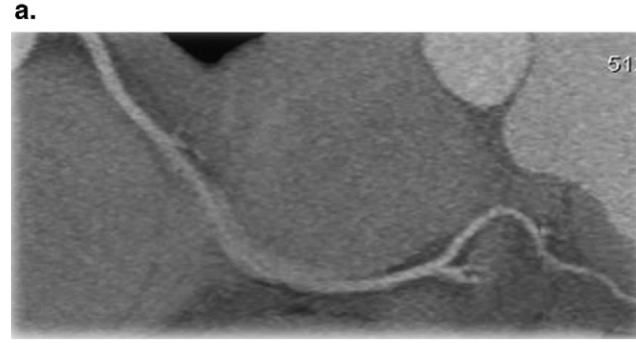

b.

Figure 4. Dependence of image quality on heart rate variability. **(a)** Standard protocol at variability of 4 beats/minute. In connection with the window of 10%, it is possible to find an optimal phase for the image. **(b)** Low-dose protocol at variability of 4 beats/minute. Because scanning is performed in a fixed phase (75%), image quality in middle segment RCA may not be optimal.

CONCLUSION

Compared with the standard protocol, the low-dose protocol results in radiation dose reduction of approximately 80%. Prospective ECG-gated CCTA with tube voltage 100 kV can be applied without loss of image quality on patients with BMI <30, but is more

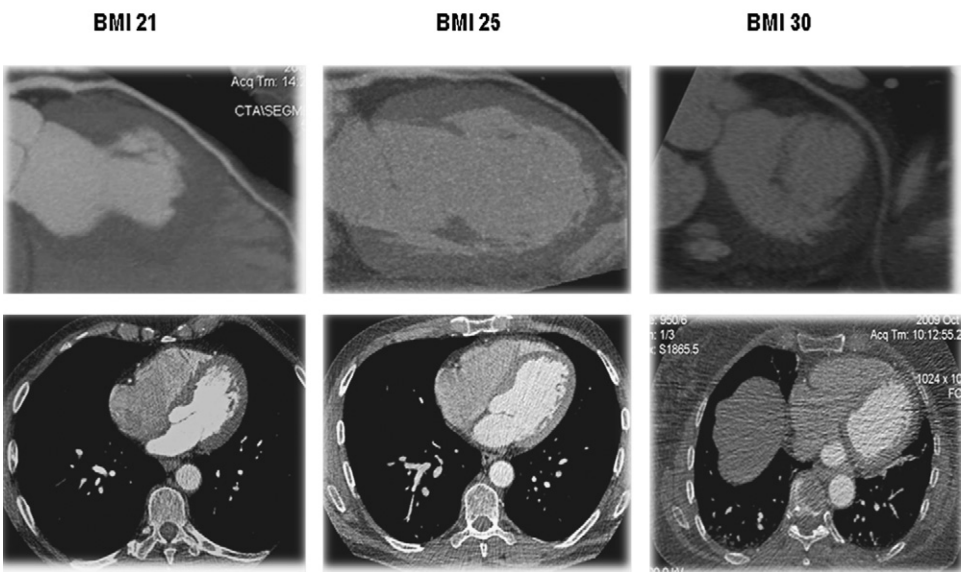

Figure 5. Dependence of image quality on body mass index (standard protocol). *Upper panel*: curved planar reformations. *Lower panel*: axial images.

sensitive to heart rate variability than the full-dose protocol.

The method described in this article is purely based on optimizing the scan condition including 100 kV and prospective ECG-gating. With the application of any iterative algorithm or alternative procedures, the patient dose may be reduced even further. Future work will be directed toward applying iterative reconstruction for further dose reduction while maintaining the highest image quality possible.

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