Potential Dose Reduction of Optimal ECG-controlled Tube Current Modulation for 256-Slice CT Coronary Angiography

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Rationale and Objectives: The purpose of this study was to design an optimized heart rate (HR)-dependent electrocardiogram (ECG) pulsing protocol for computed tomography coronary angiography (CTCA) on a 256-slice CT scanner and to assess its potential dose reduction retrospectively, based on the retrospective ECG gating data without dose modulation.

Materials and Methods: A total of 137 patients were enrolled to perform CTCA with a 256-slice scanner. Two independent radiologists graded image quality of coronary artery segments (1 = excellent, no motion artifacts; 4 = poor, severe motion artifacts) to define optimal reconstruction window in end-systolic phase, mid-diastolic phase, and the combination of both cardiac phases. According to statistical analysis for HR against image quality, four HR-depended ECG-pulsing protocols were proposed. We also demonstrated the potential dose reduction of the proposed technique.

Results: For patients with HR <59 beats/min (group 1), 60–72 beats/min (group 2), 73–84 beats/min (group 3), and >85 beats/min (group 4), the optimal reconstruction windows were at 74.1–81.3%, 73.4–82.2%, 38.3–82.3%, and 37.2–61.6% of R-R interval, respectively. The ECG-pulsing protocols with minimal radiation dose (ie, no tube current outside the pulsing window) can reduce the effective dose of CTCA by 79.5%, 75.7%, 38.3%, and 57.4% for HR groups 1 to 4, respectively. The corresponding results for reducing tube current by 80% outside the pulsing window were 63.7%, 56.6%, 32.0%, and 46.0%.

Conclusion: Through the optimization of ECG-pulsed tube-current modulation, radiation exposure can be greatly reduced, especially in patients with HR <72 beats/min or >85 beats/min.

Key Words: Coronary 256-slice CT; CT coronary angiography; ECG-controlled tube current modulation; radiation dose.

Computed tomography coronary angiography (CTCA) is highly accurate compared to invasive diagnostic catheterization (1–4). Various dose reduction techniques were introduced in CTCA to reduce exposure by approximately 25%–50% (5–7). A tube current modulation technique where the x-ray tube is turned on at predefined time points is called prospective electrocardiogram (ECG) triggering. Scheffel et al reported a mean effective dose range of 1.4–4.4 mSv for patients having heart rate (HR) range of 44–69 beats/min (8). Though this protocol can be applied to a limited number of sporadic arrhythmias (9), it is usually feasible for patients with monotonous cardiac rhythm and minimal heart rate variability (HRV). Another important strategy for dose reduction in CTCA is ECG-controlled tube current modulation (ETCM) (10). The tube current is only at maximum within the most quiescent phase of the cardiac cycle, whereas it can be reduced by 80% or more outside the pulsing window, depending if functional evaluation such as valve motion, wall motion or ejection fraction is desirable or not. A study of a dual-source 64-slice CT reported that mean effective dose of 33.4 mSv from CTCA without ETCM can be reduced to 11.0 mSv and 6.8 mSv when tube currents were set at 20% and 4% of the nominal value outside the pulsing window, respectively (11).

Radiation exposure of CTCA with ETCM technique on 64-slice and dual-source scanners has been investigated in several studies (7,10,11) that demonstrated that an effective implementation of ETCM technique is highly dependent

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on the HR of patients and the temporal resolution of CT scanner. The recently introduced 256-slice CT offers temporal resolutions with a minimum of 135 ms. This scanner also provides z-axial coverage of 80 mm, allowing an acquisition time for the whole heart as low as 5 seconds for a 120-mm z-axial coverage (12). To the best of our knowledge, no similar study for a 256-slice multidetector CT (MDCT) has been reported yet. The purpose of this study was to design and implement an optimal ECG-pulsing protocol for a 256-slice CT scanner, and evaluate its potential in radiation dose reduction.

MATERIALS AND METHODS

Patient Population

Between January 2009 and December 2010, 137 patients (86 male, 51 female; mean age 57.1 ± 9.6 years; range 32–83 years) with a variety of clinical symptoms (chest pain: 7/137; tachycardia: 1/137; coronary bypass: 2/137; coronary stent: 3/137; elevated cardiovascular risk: 9/137; followed by a positive stress test: 9/137; low to intermediate pretest probability of coronary artery disease: 106/137) were retrospectively enrolled to perform CTCA with a 256-slice scanner. The institutional review board approved the study, and all patients gave informed consent. The body mass index (BMI) for these patients was 25.6 ± 4.5 kg/m^2 (range 17.48–36.74 kg/m^2). Forty-one patients (30%) with prescan HR >90 beats/min were given beta-blocker (40–120 mg propranolol according to body weight) 1 hour before scanning to reduce their HR. Patients with previous allergic reactions to iodinated contrast media, hemodynamic instability, pregnancy, and insufficient renal function (creatinine level >1.5 mg/dL) and patients who were unable to follow breath-hold compliances were excluded (n = 26).

CT Acquisition Protocol

All CTCA examinations were performed on a 256-slice CT scanner (Brilliance iCT; Philips Medical Systems, Eindhoven, Netherlands). Nitroglycerin lingual spray was administrated for all patients in this study to minimize the difference of the diameter of coronary artery in different cardiac phases. Patients were scanned in a craniocaudal direction, covering the region from about the carina to the diaphragm. Based on the weight of the patients, we injected 70–90 mL of nonionic contrast medium (Optiray 350, Tyco Healthcare, Montreal, Quebec, Canada) into the antecubital vein of the patients at a mean flow rate of 5 mL/sec. This was followed by a chaser bolus of 30 mL saline with the same flow rate using a dual-head injector (Stellant D, Medrad, Warrendale, PA). To optimize the starting time for acquisition, an automatic bolus tracking technique was used (13). A prescan was performed at the level of the aortic root, and a 10 mm diameter circular region of interest (ROI) was placed on the ascending aorta. As soon as the signal density in the ROI exceeded 110 HU, image acquisition was initiated.

The following acquisition parameters were used in this study: 128 × 0.625 mm detector collimation; 256 × 0.625 mm slice collimation by means of a dynamic z-focal spot for double sampling; 270-ms gantry rotation time. HR-dependent pitch was set at 0.16 for patients with HR ≤62 beats/min and 0.18 for patients with HR >62 beats/min. We used a tube voltage of 120 and a varying current-time product (range 800–900 mAs) automatically according to body habitus. Full x-ray tube current was given during the whole R-R interval to assure the best image quality for the whole cardiac cycle for optimization of the reconstruction interval. The imaging time was less than 5 seconds, so each acquisition can be completed within one breathhold.

CT Data Postprocessing and Image Analysis

The matrix size of reconstructed image was 512 × 512 with a slice thickness of 0.9 mm and a slice interval of 0.5 mm. The CTCA images were reconstructed using the 180° cardiac interpolation algorithm (8) and the adaptive cardio volume approach (5), along with medium soft-tissue convolution kernel. All images were transferred to a separate workstation (Extended Brilliance Workspace 4.0, Philips) for further analysis. Thin-slab maximum intensity projections and curved multiplanar reformations were performed. Coronary artery segments were classified according to the 15-segment American Heart Association classification (14) and the intermediate artery was claimed as segment 16 if present. Coronary artery analysis was performed only on vessels with ≥1.0 mm luminal diameter at their origin. Image quality of each segment was determined by two independent and blinded radiologists using 4-point Likert ranking scale (1 = excellent, no motion artifacts, 2 = good, minor motion artifacts, 3 = moderate, mild motion artifacts; 4 = poor, severe motion artifacts). A score of 3 or lower was considered with acceptable image quality for routine clinical diagnostic purposes (Fig 1).

Twenty datasets were first reconstructed in 5% steps from 0% to 95% of the R-R interval, and evaluated by two radiologists to determine preliminary optimal R-R intervals. Further reconstructions were performed with 1% step in those selected R-R intervals for the radiologists to determine the optimal reconstruction intervals for systolic, diastolic, and the combination of systolic and diastolic reconstructions. The optimal reconstruction interval used in this study was centered at the mean of optimal reconstruction time points with a symmetric width of 4 standard deviations (SD), (ie, 95% confidence interval [CI]).

Statistical Analysis

Interobserver agreement for the position of the optimal reconstruction interval was calculated using Cohen's kappa statistic. The influence of image quality versus HR was assessed by means of Pearson's correlation coefficient. Then, linear regressions between HR and image quality were performed to classify patients into different HR groups based on the intersection points of the regression lines. For each

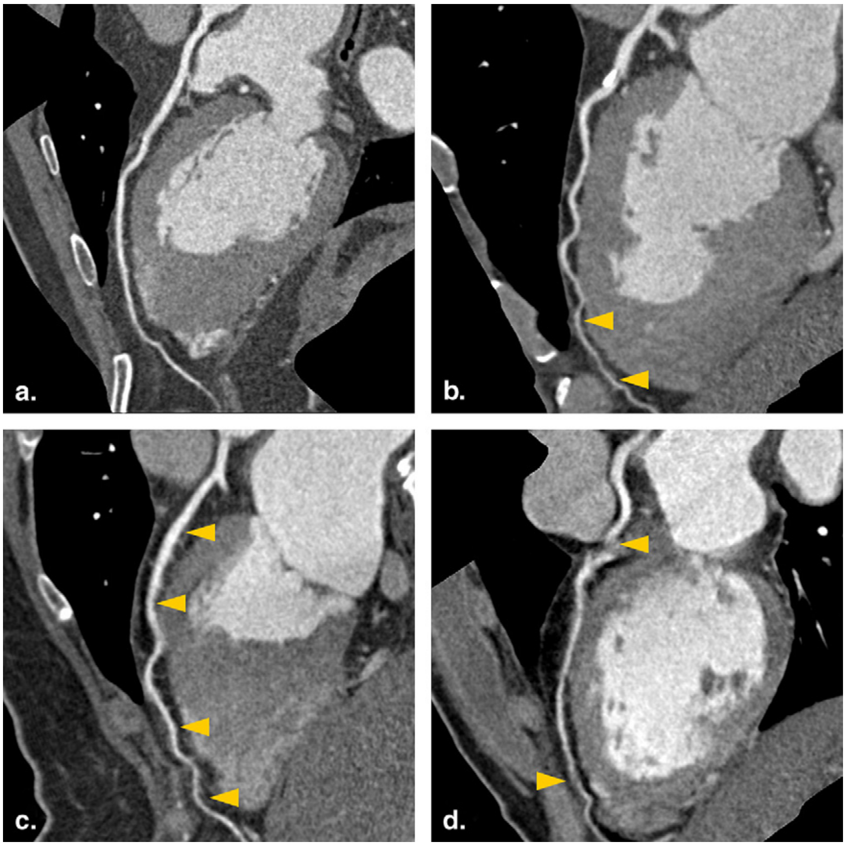

Figure 1. Curved multiplanar reconstruction images of LAD illustrate the use of four-point image quality score. **(a)** Patient with mean heart rate (HR) of 67 beats/min (SD, 0.7 beats/min). Image reconstructed at 75% of the R-R interval shows no motion artifact in all segment of LAD (score 1). **(b)** A patient with mean HR of 78 beats/min (SD, 1.1 beats/min). Image reconstructed at 78% of R-R interval shows minor motion artifacts (score 2) in the distal segment of LAD that cause minor blurring of the wall. **(c)** A patient with mean HR of 78 beats/min (SD, 1.7 beats/min). Image reconstructed at 45% of R-R interval shows mild motion artifacts (score 3) in the middle and distal segment of LAD, with moderate blurring of the vessel outline. **(d)** A patient with mean HR of 86 beats/min (SD, 0.7 beats/min). Image reconstructed at 80% of R-R interval shows severe artifacts (score 4) with discontinuity of the proximal and distal segment of LAD, causing nondiagnostic image quality. LAD, descending coronary artery.

resultant HR group, we compared the mean image quality scores for optimal systolic-, diastolic-, and combined-phases reconstructions using the Wilcoxon's signed-rank test, and the phase with the best image quality was applied with full tube current during the tube current modulation. In addition, the mean and SD of the optimal reconstruction phase were calculated and used to design the timing and width of the pulsing window for tube current modulation, respectively. The pulsing window was centered at the mean of optimal reconstruction phases over all segments. Its coverage is composed of the half-scan time in one cardiac cycle (135 ms) and an extra temporal padding with width of 95% CI of optimal reconstruction interval (±2 SD). A P value of <.05 was considered statistically significant. All statistical analysis was performed using NCSS software (NCSS version 2007, NCSS, Kaysville, UT).

Radiation Dose

The dose-length product represents an indicator of the integrated radiation dose of an entire CT examination, obtained by multiplying the volume CT dose index (CTDI_{vol}) by the length of the patient being scanned. We obtained the CTDI_{vol} and scan length for each patient from the scanner-generated report. A reasonable approximation of the effective patient dose of the proposed HR-dependent ECG-pulsing protocols can be obtained by multiplying the dose-length product by a conversion factor for the chest ($k = 0.017$ mSv/mGy^{-1}/cm^{-1}) (15).

RESULTS

The average HR of the 137 patients during scanning was 73.5 beats/min (SD, 7.5 beats/min; range 46–96 beats/min) with the HRV of 1.3 beats/min (SD, 0.7 beats/min; range 0–4.2 beats/min). A total of 1800 coronary segments were evaluated and 301 segments were not evaluable because of the anatomical variations. The κ statistics were 0.78 in systolic reconstruction and 0.82 in diastolic reconstruction, indicating good interobserver agreement. The optimal systolic and diastolic reconstruction intervals were at 43.0 ± 3.8% and 78.0 ± 3.7% of the R-R interval, respectively. Image quality for three reconstruction schemes for each segment was summarized in Table 1. Image quality score for reconstruction from both systolic and diastolic phases was improved to 1.5 ± 0.4, and showed statistically significant difference as compared to systolic- or diastolic-only reconstruction ($P < .005$). Regarding to the influence of HR on image quality score (Fig 2), no significant correlation was observed between HR and image quality in systolic phase. On the other hand, we found significant correlation between HR and image quality for diastolic reconstruction and in reconstruction from both cardiac phases. All patients were stratified into four HR groups according to the crossover points of regression lines from Figure 2d: ≤59 beats/min (group 1, $n = 10$); 60–72 beats/min (group 2, $n = 59$); 73–84 beats/min (group 3, $n = 57$); ≥85 beats/min (group 4, $n = 11$). The demographic data ae listed in Table 2. The results from analysis

TABLE 1. Overall Image Quality of Optimal Reconstructions in Systolic Phase (S), Diastolic Phase (D), and Combined Systolic and Diastolic Phases (S+D)

Best Image Obtained in	S	D	S+D
No. of segments	1800	1800	1800
Overall image quality	1.8 ± 0.5	1.8 ± 0.3	1.5 ± 0.4
Score 1 (%)*	31.6 (569/1800)	38.1 (686/1800)	51.2 (922/1800)
Score 2 (%)	58.6 (1055/1800)	49.8 (896/1800)	47.2 (850/1800)
Score 3 (%)	9.8 (176/1800)	10.7 (192/1800)	1.6 (28/1800)
Score 4 (%)	0.0 (0/1800)	1.4 (26/1800)	0.0 (0/1800)

*Data in parentheses are numbers of segments used to calculate the percentages.

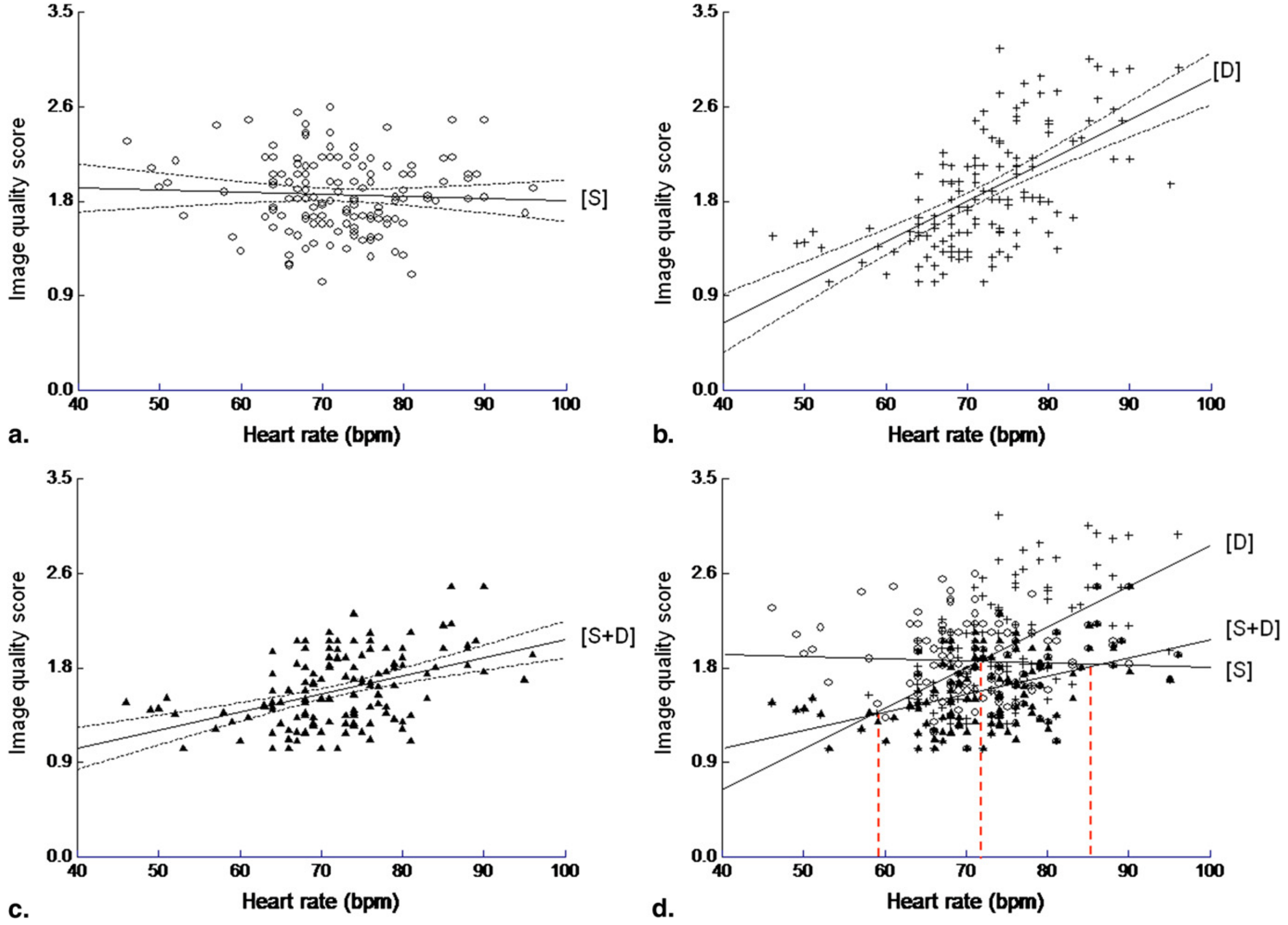

Figure 2. Scatter plots of image quality score in relation to heart rate (HR). Linear regression for image quality scores in **(a)** systolic reconstructions, **(b)** diastolic reconstructions, and **(c)** combined systolic and diastolic reconstruction versus HR. Middle lines show linear regression, and upper and lower lines show 95% confidence interval. **(d)** Fusion of data shown in **(a,b,c)**. Note that lines represent calculated linear regressions for image quality in systole (*hollow circles*), diastole (*crosses*), and the combination of both cardiac phases (*solid triangles*).

of variance test showed no significant differences among four groups with respect to demographic data, except the average HR ($P < .05$).

The image quality and results of statistical comparisons of three reconstruction schemes are shown in Figure 3. The optimal systolic reconstruction windows for HR groups 1–4 were at 41.0 ± 2.1%, 43.5 ± 2.8%, 45.1 ± 3.4%, and 49.4 ± 6.1% of the R-R interval, respectively. The optimal diastolic reconstruction windows for HR groups 1–4 were at 77.7 ± 1.8%, 77.8 ± 2.2%, 77.1 ± 2.6%, and 74.8 ± 12.0% of the R-R interval, respectively. Overall image quality in diastolic reconstruction was better than that in systolic reconstruction for patients with HR <72 beats/min. Reconstruction from both systolic and diastolic phases performed best in all HR groups. Because the reconstructed image quality provided by diastolic phase and both cardiac

TABLE 2. Demographic Data of Patients in Four HR Groups

Characteristic	HR ≤59 beats/min	HR 60–72 beats/min	HR 73–84 beats/min	HR ≥85 beats/min
No. of patients	10	59	57	11
Age (y)	68.3 ± 9.5	55.7 ± 10.6	55.9 ± 8.5	60.3 ± 6.9
Female/male	3/7	15/44	29/28	4/7
Body mass index (kg/m^2)	26.1 ± 3.4	26.4 ± 4.4	24.7 ± 3.3	25.8 ± 3.5
Average heart rate (beats/min)	57.3 ± 2.5	67.3 ± 2.7	76.3 ± 3.1	87.2 ± 1.9
Heart rate variability (beats/min)	1.2 ± 0.2	1.4 ± 0.8	1.3 ± 0.6	1.0 ± 0.5
Scan length (mm)	129.6 ± 13.3	131.3 ± 13.6	128.7 ± 13.5	127.0 ± 16.2
Scan time (seconds)	4.6 ± 0.6	4.9 ± 0.3	5.0 ± 0.3	5.0 ± 0.5
CTDI$_{vol}$ (mGy)	66.8 ± 11.2	61.0 ± 12.1	58.8 ± 8.8	57.1 ± 4.7

CTDI$_{vol}$, volume computed tomography dose index.

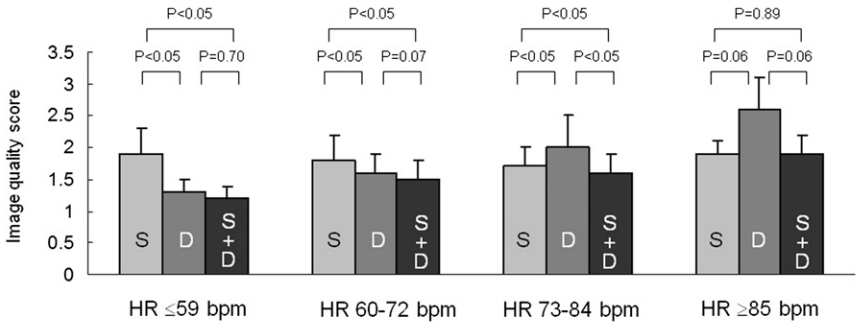

Figure 3. Image quality scores of reconstructions in systolic phase (S), diastolic phase (D), and from both cardiac phases (S+D) for four heart rate groups.

phases was not statistically different in groups 1 and 2, we chose the optimal diastolic phase as the ECG pausing protocol for these two groups to further reduce radiation dose. At HR 73–84 beats/min, the image quality of reconstruction from both systolic and diastolic phases was significantly better than the others ($P < .05$). Thus, reconstruction from both cardiac phases was defined as the ECG pausing protocol in group 3. For group 4, the systolic phase was picked as the ECG pausing protocol to further reduce radiation dose as image scores of reconstructions in systolic phase and combined cardiac phases were not statistically different. The overall image quality scores of best reconstruction scheme were 1.3 ± 0.2, 1.6 ± 0.3, 1.6 ± 0.3, and 1.9 ± 0.2 for groups 1–4, respectively. Figure 4 shows the optimized HR-dependent ECG-pulsing protocols, called narrow pulsing window, with a tube current outside the ECG-pulsing window of 0% (ie, the minimal radiation dose achievable). Considering the time required to ramp down and up the x-ray tube, it is more practical for Group 3 to use a wide pulsing window by merging two narrow pulsing windows shown in Figure 4c in real clinical situations. In comparison to the narrow pulsing window, there is only a 2% increase in radiation exposure using the proposed wide pulsing window. Based on theoretical calculations, the proposed ECG-pulsing protocol with 0% tube current outside pulsing window can reduce the effective dose by 79.5% (from 14.6 to 3.0 mSv), 75.7% (from 13.6 to 3.3 mSv), 38.3% (from 12.8 to 7.9 mSv), and 57.4% (from 12.2 to 5.2 mSv) for groups 1 through 4, respectively. The corresponding dose reduction for reducing tube current by 80% outside the pulsing window, with functional analysis feasible, are 63.7% (from 14.6 to 5.3 mSv), 56.6% (from 13.6 to 5.3 mSv), 32.0% (from 12.8 to 8.9 mSv), and 46.0% (from 12.2 to 6.6 mSv) (Table 3).

DISCUSSION

The impressive image quality and non-invasive nature of MDCT lead to the growth of cardiac CT in the past few years. Along with the raise in popularity of MDCT in clinical practice, there has been a safety concern regarding its radiation dose. Applying ETCM technique to control x-ray tube real-time has been demonstrated to be an efficient way for reducing radiation exposure in 16-slice, 64-slice, and dual-source CT (6–8,10,11). Improvement on detector coverage and temporal resolution can significantly reduce the scan time required for a CTCA scan and thus lead to less susceptibility to motion artifacts and HRV (16). The 256-slice MDCT has a larger anatomical coverage per rotation but a slower gantry rotation time (0.27 seconds) when compared with a dual-source CT. Based on the results of our previous work, no significant influence of HRV on image quality has been observed (17). Moreover, this CT system provides a 120 kW x-ray tube power to facilitate imaging of obese patients with BMI >30 kg/m^2. The overall diagnostic evaluability of our results from patients with BMI ranging from 17.48 to 36.74 kg/m^2 was 100% in systolic reconstruction and 98.4% in diastolic reconstruction (Table 1).

The optimal reconstruction phase has been known to be affected by the temporal resolution of a CT scanner. For

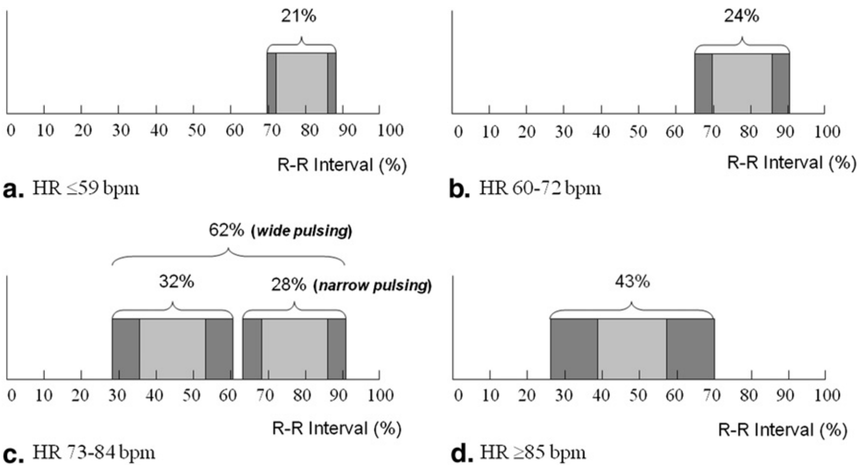

Figure 4. Proposed electrocardiogram (ECG) pulsing window with no exposure outside the pulsing window for four heart rate groups. Its coverage is composed of the half-scan time in one cardiac cycle (*light gray region*) and an extratemporal padding with width of 95% CI of optimal reconstruction interval (*dark gray region*). The percentage shown is the ratio of radiation dose of proposed ECG pulsing normalized with the one with no ECG pulsing.

TABLE 3. Estimated Effective Dose of Retrospectively Gated CTCA without Tube Current Modulation and with the Proposed Model

	HR ≤59 beats/min	HR 60–73 beats/min	HR 74–84 beats/min	HR ≥85 beats/min
Optimal pulsing windows* (mean ± 2 standard deviation %)	D 77.7 ± 3.6	D 77.8 ± 4.4	S 45.1 ± 6.8 D 77.1 ± 5.2	S 49.4 ± 12.2
With tube current modulation				
20% tube current (mSv)[†]	5.3	5.3	8.7/8.9[§]	6.6
0% tube current (mSv)[‡]	3.0	3.3	7.7/7.9[‡]	5.2
No tube current modulation (mSv)	14.6	13.6	12.8	12.2

D, diastolic phase; HR, heart rate; S, indicates systolic.

*The optimal pulsing windows were centered at the mean optimal reconstruction time points with a symmetric width of ± 2 standard deviations (ie, 95% confidence interval).

[†] Tube current outside the pulsing window was reduced to 20% of the full tube current.

[‡] No exposure was applied outside the pulsing window.

[§] Values are the estimated doses of narrow pulsing window (former) and wide pulsing window (later).

a 16-slice MDCT having a temporal resolution of 165 ms, systolic reconstruction is recommended for patients with HR >67 beats/min (18), whereas the diastolic reconstruction was preferred for HR ≤80 beats/min for dual-source CT with 83 ms temporal resolution (18,19). Our results suggested that diastolic reconstruction may be used for patients with HR up to 72 beats/min to achieve high quality CTCA on the 256-slice MDCT. Commonly, image reconstruction in cardiac CT is performed in mid diastole, the most quiescent phase over the cardiac cycle (20,21). However, the diastolic rest period dramatically shortens with increasing HR and even ceases to exist at HR around 80 beats/min (20–23). Hence, although a temporal resolution of about 135 ms should be appropriate for motion-free imaging in the diastolic phase for HR up to 90 beats/min (16,17), our data indicated a significant decrease in image quality with increasing HR. On the other hand, the end systolic period, the second quiescent cardiac phase, remains relatively constant with increasing HR (23), so the image quality of systolic reconstruction is generally considered to be less affected by HR (24). Because the optimal reconstruction window varies with HR, the ECG-pulsing protocol needs to be HR-dependent to reduce radiation dose without compromising diagnostic imaging quality. For example, for patients in group 3, combined systolic and diastolic phases are suggested for optimal reconstructions as their image quality scores are significantly better than the sole systolic phase reconstruction, though the systolic reconstruction itself provides acceptable image quality. Undoubtedly, the best image quality was obtained when no ECG pulsing was applied, but it is also the protocol having highest radiation exposure. Thus, HR-dependent ECG-pulsing window was designed to achieve approximately the same level of image quality for no ECG pulsing, whereas radiation exposure can be reduced. As seen in Figure 3, the reduction in radiation exposure is considerable in patients with HR <72 beats/min or >85 beats/min. This finding is consistent with a previous study by Weustink et al (11), discussing ECG modulation strategy in a dual-source CT. In another study, for patient with HR of 72–85 beats/min, although the image quality in diastole became affected by the shortening of diastolic rest phase, the 135-ms temporal resolution provided by this 256-slice MDCT permits imaging at mid-diastolic period for patients with HR up to 75 beats/min (16). This may explain why the combined use of systolic and diastolic reconstructions has significantly lower image quality score for group 3.

A recent study evidenced that prospective ECG-triggering with 256-slice scanner can achieve a dose reduction up to 76%

(25). But this mode is only reliable for patients with stable and slow HR (57.1 ± 7.2 beats/min). For our proposed method with no tube current outside the pulsing window, same level of dose reduction is achieved in patient with low HR (group 1: 3.0 mSv; group 2: 3.3 mSv), whereas dose reduction can also be realized on patients with higher HR (group 3: 7.9 mSv; group 4: 5.2 mSv). In addition, when the tube current outside the pulsing window is set at 20%, the data set can then be used for cardiac functional analysis, such as valve motion, wall motion, and ejection fraction, demonstrating its wide application for clinical practice.

There are a few limitations of our study. Because our main theme was to determine the optimal pausing protocols, we presented the evaluability of the system only based on the clinical CT assessment, and there are currently no catheter angiography data available for validation (ie, comparison between the optimized acquisition techniques with the conventional coronary angiography). Also, we only evaluated the coronary image quality based on subjective image quality based on motion artifacts interpretation. Other image quality measurements, such as signal-to-noise ratios and calcium-related blooming artifacts, would be desirable to thoroughly investigate the impact of ECG-pulsing protocol on coronary motion artifacts. Our results showed that the use of HR-dependent ECG-pulsing windows could achieve a significant dose reduction in 256-slice MDCT based on theoretical calculations. Further testing is needed to demonstrate the efficacy of these protocols in real clinical situations. Finally, we do not evaluate the effect of other dose reduction strategies and their associated image quality. Modification in scanning parameters, such as lower tube voltage and tube current, is expected to achieve further dose reduction.

CONCLUSIONS

Optimal reconstruction window for a cardiac cycle strongly depends on the HR of patients and temporal resolution of a CT scanner. We have proposed HR-dependent ECG-pulsing protocols for a 256-slice MDCT. Through the optimized ETCM strategy, the radiation exposure can be potentially reduced by 38.3% to 79.5%. Further study to confirm the diagnostic accuracy as compared to coronary artery angiography is warranted.

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