

Prospectively Gated Transverse Coronary CT Angiography versus Retrospectively Gated Helical Technique: Improved Image Quality and Reduced Radiation Dose¹

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Purpose:

To retrospectively compare image quality, radiation dose, and blood vessel assessability for coronary artery computed tomographic (CT) angiograms obtained with a prospectively gated transverse (PGT) CT technique and a retrospectively gated helical (RGH) CT technique.

Materials and Methods:

This HIPAA-compliant study received a waiver for approval from the institutional review board, including one for informed consent. Coronary CT angiograms obtained with 64-detector row CT were retrospectively evaluated in 203 clinical patients. A routine RGH technique was evaluated in 82 consecutive patients (44 males, 38 females; mean age, 55.6 years). The PGT technique was then evaluated in 121 additional patients (71 males, 50 females; mean age, 56.7 years). All images were evaluated for image quality, estimated radiation dose, and coronary artery segment assessability. Differences in image quality score were evaluated by using a proportional odds logistic regression model, with main effects for three readers, two techniques, and four arteries.

Results:

The mean effective dose for the group with the PGT technique was 2.8 mSv; this represents an 83% reduction as compared with that for the group with the RGH technique (mean, 18.4 mSv; $P < .001$). The image quality score for each of the arteries, as well as the overall combined score, was significantly greater for images obtained with PGT technique than for images obtained with RGH technique. The combined mean image quality score was 4.791 for images obtained with PGT technique versus 4.514 for images obtained with RGH technique (proportional odds model odds ratio, 2.8; 95% confidence interval: 1.7, 4.8). The percentage of assessable coronary artery segments was 98.6% (1196 of 1213) for images obtained with PGT technique versus 97.9% (1741 of 1778) for images obtained with RGH technique ($P = .83$).

Conclusion:

PGT coronary CT angiography offers improved image quality and substantially reduced effective radiation dose compared with traditional RGH coronary CT angiography.

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Coronary computed tomographic (CT) angiography performed with multi-detector row CT is an accurate method for the noninvasive detection of coronary artery disease (CAD) (1–14). Coronary CT angiography is performed with retrospectively gated helical (RGH) data acquisition in which the patient and table move through the gantry at a steady speed. Although the RGH technique has proved to be accurate, it is hindered by both high effective radiation dose and difficulty in handling cardiac ectopy.

Radiation dose is a concern for all cardiac imaging studies in which ionizing radiation is used. The reported effective radiation dose in conventional coronary angiography ranges from 3.1 to 9.4 mSv, whereas researchers in most studies report that the coronary CT angiographic dose is even higher (15–20). Reported effective radiation dosage in recent studies with the use of 64-detector row CT have ranged from 9.5 to 21.4 mSv, more than the previously reported doses from 16-detector row CT studies (9,12,13,21) (Table 1). The effective doses reported for coronary CT angiography performed with dual-source CT systems are also relatively high, ranging from 8 to 16.1 mSv (22–24). Previous attempts to develop methods to reduce the radiation dose with coronary CT angiography have primarily involved the use of electrocardiogram (ECG)-controlled tube current modulation or reduction of tube current or tube voltage (25,26).

Advances in Knowledge

- Prospectively gated transverse (PGT), compared with retrospectively gated helical (RGH), coronary multi-detector row CT angiography improved image quality ($P < .001$) and reduced effective radiation dose ($P < .001$) to the patient.
- Coronary CT angiography performed with the PGT technique has coronary artery assessability rates similar to those of coronary CT angiography performed with the RGH technique.

Hsieh et al (27) recently reported an approach for coronary CT angiography with use of a combined step-and-shoot transverse data acquisition, an incrementally moving table, adaptive ECG triggering, an improved image reconstruction algorithm, and multiphase reconstruction capability (Fig 1). We refer to this method as prospectively gated transverse (PGT) coronary CT angiography. The method takes advantage of the large 40-mm (64×0.625 mm) volume coverage available with the 64-detector row CT scanner that enables complete coverage of the heart in three or four incremental 40-mm acquisitions. By using this technique, the table is stationary during image acquisition and then moves to the next location for another scan that is initiated by the subsequent cardiac cycle. The result is very little overlap between the scans, substantial reduction in radiation dose, and more robust and adaptive ECG gating.

Thus, the purpose of our study was to retrospectively compare image quality, radiation dose, and blood vessel assessability for coronary artery CT angiograms obtained with a PGT CT technique and an RGH CT technique.

Materials and Methods

Our Health Insurance Portability and Accountability Act-compliant study received a waiver from the institutional review board, including a waiver of informed consent. Angiograms from coronary CT examinations performed from August through November 2006 were considered for inclusion. Demographic, physiologic, and medical history information was recorded (J.P.E., R.S.J., J.L.L.) from the examination history, questionnaire, and both nursing and technologists' notes.

Three authors (J.H., J.H.L., and C.C.M.) are employees of GE Health-

care, manufacturer of the CT system used in this study. The other (non-GE Healthcare employee) authors had control of the data and information that might present a conflict of interest for the employee authors.

Patients

Eighty-two consecutive RGH coronary CT angiographic procedures performed in 82 patients (44 males and 38 females; mean age, 55.6 years) were initially obtained during the study period by using a routine RGH coronary CT angiographic protocol. All examinations were performed for clinical reasons. After initially optimizing imaging parameters, we included 121 (92.4%) (71 males and 50 females; mean age, 56.7 years) of the next 131 consecutive clinical patients presenting for coronary CT angiography, as they met our inclusion criteria (heart rate, <70 beats per minute; observed heart rate fluctuation, <10 beats per minute during observation at the scanner prior to performance of the coronary CT angiographic sequence).

Multi-Detector Row CT

All CT examinations were performed with a 64-detector row CT unit (Light-

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Abbreviations:

BMI = body mass index
CAD = coronary artery disease
ECG = electrocardiogram
OR = odds ratio
PGT = prospectively gated transverse
RGH = retrospectively gated helical

Author contributions:

Guarantors of integrity of entire study, J.P.E., J.L.L.; study concepts/study design or data acquisition or data analysis/interpretation, all authors; manuscript drafting or manuscript revision for important intellectual content, all authors; manuscript final version approval, all authors; literature research, J.P.E., J.L.L., C.C.M., J.H.; clinical studies, J.P.E., E.L.B., B.A.U., C.A.C., J.L.L., R.S.J., J.H.; experimental studies, E.L.B., J.H.; statistical analysis, J.P.E., E.L.B., C.C.M.; and manuscript editing, J.P.E., B.A.U., C.A.C., R.S.J., C.C.M., J.H., J.H.L.

See Materials and Methods for pertinent disclosures.

Implication for Patient Care

- The use of PGT, as compared with RGH, coronary CT angiography decreases the effective radiation dose to the patient by 83%.

Speed VCT XT, software version 7.1; GE Healthcare, Milwaukee, Wis), with a rotation time of 350 msec, fixed single-sector reformation with a temporal resolution of 175 msec, detector aperture of 0.625 mm, scan field of view of 25 cm, and tube voltage of 120 kV. The scan sequence included a scout scanogram, a low-dose transverse scout or calcium-scoring scan, a test-bolus scan, and a coronary angiogram. A low-dose transverse scout scan is used to determine the position of the left main coronary artery and cardiac apex for prescription of the coronary angiographic sequence, when a calcium-scoring study is not performed. Criteria for performing a calcium-scoring sequence included age older than 45 years, no coronary stent placed, no prior coronary angiography performed, and no calcium-scoring study performed within the past 12 months; 69% of patients underwent a calcium-scoring study.

A dual-headed injector (Optivan-tage DH; Mallinckrodt, St Louis, Mo) was used for all coronary CT angiographic studies. For both PGT and RGH studies, a test-bolus scan was obtained at the level of the aortic root. Sequential scans were obtained every 2 seconds for 30 seconds after administration of the test bolus of 20 mL iodixanol 320 (Visipaque; GE Healthcare, Princeton, NJ) at 5.5 mL/sec. The diagnostic angiogram included an area 20 mm above the left main orifice to 20 mm below the apex of the heart. All scans were obtained in a cranial-caudal direction. The timing of the main injection of contrast medium (50–80 mL iodixanol 320 at 5.5 mL/sec) was determined by the time to peak enhancement from the test bolus plus 8 seconds to allow for coronary artery filling.

A dose of 50–100 mg of a β -adrenergic blocking agent, metoprolol (Mylan Pharmaceuticals, Morgantown, WV), was administered orally at 45–60 minutes before CT examination if the patient's resting heart rate exceeded 60 beats per minute and there was no contraindication to the use of a β -adrenergic blocking agent. In seven of the patients undergoing RGH CT angiography

and eight of the patients undergoing PGT CT angiography, oral medication was supplemented with 5-mg intravenous aliquots of metoprolol administered at 5-minute intervals up to a maximum total intravenous dose of 20 mg.

RGH Technique

A standard RGH technique was performed by three technologists, including one author (J.L.L.), for the RGH technique group (Table 2). The tube current

was selected by one of three technologists, each experienced in performing from 300 to 4000 coronary CT angiographic examinations. The selected tube current ranged from 349 to 771 mA, depending on the patient's body mass index (BMI) and chest circumference as determined by the technologist's prior experience. ECG modulation was used in all patients (100% peak tube current during the middle of diastole and 80% reduction during systole).

Table 1

Comparison of Reported Effective Dose at Coronary CT Angiographic Examinations by Using Multi-Detector Row and Dual-Source CT Systems with and without ECG Modulation

Study	Scanner Type	Dose (mSv)	
		Without ECG Modulation	With ECG Modulation
Hunold et al (3)	16 detector row	10.9–13.0	...
Morin et al (6)	16 detector row	9.3–11.3	...
Flohr et al (4)	16 detector row	5.7–10.5	2.9–7.4
Trabold et al (5)	16 detector row	8.1–10.9	4.3–5.6
Raff et al (13)	64 detector row	...	13–18
Leber et al (9)	64 detector row	...	10–14
Mollet et al (12)	64 detector row	...	15.2–21.4
Francone et al (21)	64 detector row	...	9.5
Weustink et al (22)	64 dual source	...	11.1–16.1
Ropers et al (23)	64 dual source	...	8–12

Note.—In all studies, the RGH technique was used.

Figure 1

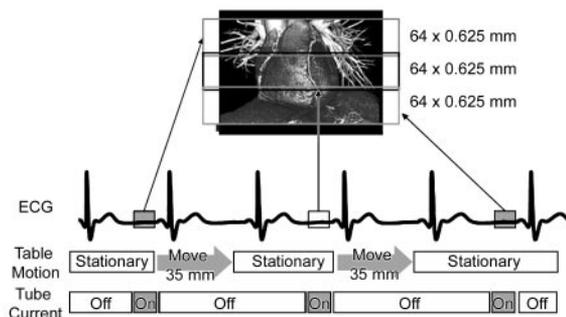


Figure 1: PGT technique relies on combined approach with transverse data acquisition, adaptive ECG triggering, incrementally moving table, and multiphase image reconstructions. Table is stationary during acquisition of 40-mm coverage (64 detector rows and 0.625-mm section thickness [64 × 0.625 mm]) group of transverse scans and then moves 35 mm, allowing a 5-mm overlap of image groups, to the next location for another scan that is initiated by the subsequent normal cardiac cycle. An adaptive prediction algorithm is used for dynamic prediction of the heart rate for the next cardiac cycle instead of using a single heart rate for the entire study.

The pitch was determined automatically by the system and is not user defined in the cardiac helical mode; it ranged from approximately 0.2 to 0.3, depending on heart rate. Images were reconstructed throughout the cardiac cycle in 10% increments. A cardiac-specific noise reduction filter (C2) was applied to the images prior to reconstruction.

PGT Technique

We used PGT coronary CT angiographic software (Snapshot Pulse; GE Healthcare, Milwaukee, Wis) that had already received Food and Drug Administration clearance (Fig 1). Only single-sector reformations are available; therefore, we used an upper limit of 70 beats per minute, following attempted administration of β -adrenergic blocking agents, as a contraindication to the use of the PGT technique.

The scan was prescribed by using three to five incremental 64×0.625 -mm (40-mm volume coverage) image groups, requiring two to four incremental table

movements of 35 mm, with a 5-mm overlap. The minimum interscan delay was approximately 1.0 second; this protocol normally requires skipping a cardiac cycle between acquisitions of successive image groups. The tube current was selected by one of three technologists (as with the RGH technique), and it ranged from 300 to 800 mA, depending on the patient's BMI and chest circumference, as determined by the technologist's prior experience. No noise reduction filters were available for use with the PGT studies. The minimum scan time at each transverse location is 230 msec (180° plus a fan angle), which translates to an effective temporal resolution of 175 msec with half-scan weighting.

The prescribed phase for data acquisition was 75% of the cardiac cycle (middle of diastole) for all subjects. Additional padding of the tube-on time was used, depending on the amount of perceived beat-to-beat variability (Fig 2). This technique turns the tube on prior to, and leaves it on after, the minimum required

230 msec. Padding allows the reconstruction to adapt to minor heart rate variations and produce consistent image quality, because the reconstruction window can be modified retrospectively to ensure an identical cardiac phase from scan to scan. For example, when the heart rate fluctuates by 10% from beat to beat (decreases from 60 to 54 beats per minute or increases from 60 to 66 beats per minute), then $\pm 10\%$ of phase (100 msec) padding is used to ensure that images during the prescribed phase location are acquired for all table locations. In this example, if the prescribed phase was 75% of the cardiac cycle, then images are captured during phases of 65%–85% of the cardiac cycle and images from multiple phases can be reconstructed. Actual padding in the study ranged from 0 msec in patients with very stable heart rates to 100 msec in patients with less stable heart rates; this padding value was chosen by the technologist on the basis of observation of the ECG waveform.

Radiation Dose

Radiation dose estimates for CT examinations of the heart are expressed by using the volume CT dose index in grays, the dose-length product in milligray-centimeters, and effective dose in millisieverts (6,28–30). The dose-length product is defined as the volume CT dose index multiplied by scan length and is an indicator of the integrated radiation dose of an entire CT examination. A reasonable approximation of the effective dose was obtained by multiplying dose-length product by a conversion factor, k (in millisieverts per milligray per centimeter), that varies depending on the body region that is imaged. Effective dose was then calculated by using a k value of $0.017 \text{ mSv} \cdot \text{mGy}^{-1} \cdot \text{cm}^{-1}$ (30). For this study, one author (R.S.J.) recorded the volume CT dose index and dose-length product generated by the CT system for each CT angiographic acquisition series.

Data Analysis

Coronary segments were defined according to American Heart Association guidelines (31). All reformatted images were evaluated and classified by three indepen-

Table 2

Comparison of Parameters for RGH and PGT Techniques

Parameter	RGH Technique	PGT Technique
Timing examination		
Nonionic contrast agent dose (mL)	20	20
Normal saline dose (mL)	50	50
Injection rate (mL/sec)	5.5	5.5
Diagnostic examination		
Nonionic contrast agent dose (mL)	50–80	50–80
Normal saline dose (mL)	50	50
Injection rate (mL/sec)	5.5	5.5
Tube voltage (kV)	120	120
Tube current (mA)*	349–771 (647)	300–800 (508)
Temporal resolution (msec)	175	175
z-Axis coverage (mm) [†]	137.6 \pm 11.3	128.2 \pm 18.90
Thickness and reconstruction interval	0.625	0.625
Other*	ECG modulation, 100% peak, 20% off	Padding, 0–100 msec (30 msec)
Reconstruction phases	5%–95%	As available
Heart rate (beats/min) [†]	58.6 \pm 7.2	56.9 \pm 6.9
No. of patients in whom β -adrenergic blocking agents were used [‡]	71/82 (87)	110/121 (91)
Scan time (sec) [†]	5.66 \pm 0.92	4.22 \pm 0.92
X-ray-on time (sec) [†]	5.66 \pm 0.92	0.88 \pm 0.16

* Values in parentheses are means.

[†] Data are the mean \pm standard deviation.

[‡] Numbers in parentheses are percentages.

dent readers (J.P.E., B.A.U., and E.L.B., each with experience interpreting images from 500 to 3000 coronary CT angiographic examinations) who were blinded to patient identity. Available images included transverse source images, curved multiplanar reformations, and thin-slab maximum intensity projections. Readers had access to images obtained during all available cardiac phases. Image evaluation and image processing were performed with an independent three-dimensional workstation equipped with software designed for use with the workstation (Advantage Windows with CardIQ software, version 4.3; GE Healthcare, Milwaukee, Wis). Because with the RGH scans more reconstructed phases were available than were available with the PGT scans, the readers could determine the scanning technique used.

For each coronary artery, the readers assessed image quality semiquantitatively by using a previously described five-point ranking scale (32). In this scale, a score of 5 indicated that there were no motion artifacts and there was a clear delineation of the artery; a score of 4, that there were minor artifacts and mild blurring; a score of 3, that there were moderate artifacts and moderate blurring without structure discontinuity; a score of 2, that there were severe artifacts and doubling or discontinuity in the course of the segment; and a score of 1, that the image was not evaluable and blood vessel structures were not differentiable. Examples of each score were provided to the readers prior to assigning a score to the images from the examinations. For coronary artery assessability, a score of 2 or less was an indication that the artery was considered nonassessable. Coronary stenoses were determined by using a 50% diameter reduction threshold value to classify a stenosis as significant; this value was determined by comparing the narrowest diameter with the diameter of the nearest normal lumen.

Statistical Analysis

Differences between imaging parameters for the two patient groups were tested by using unpaired *t* tests at the 95% confidence level (two tailed). We

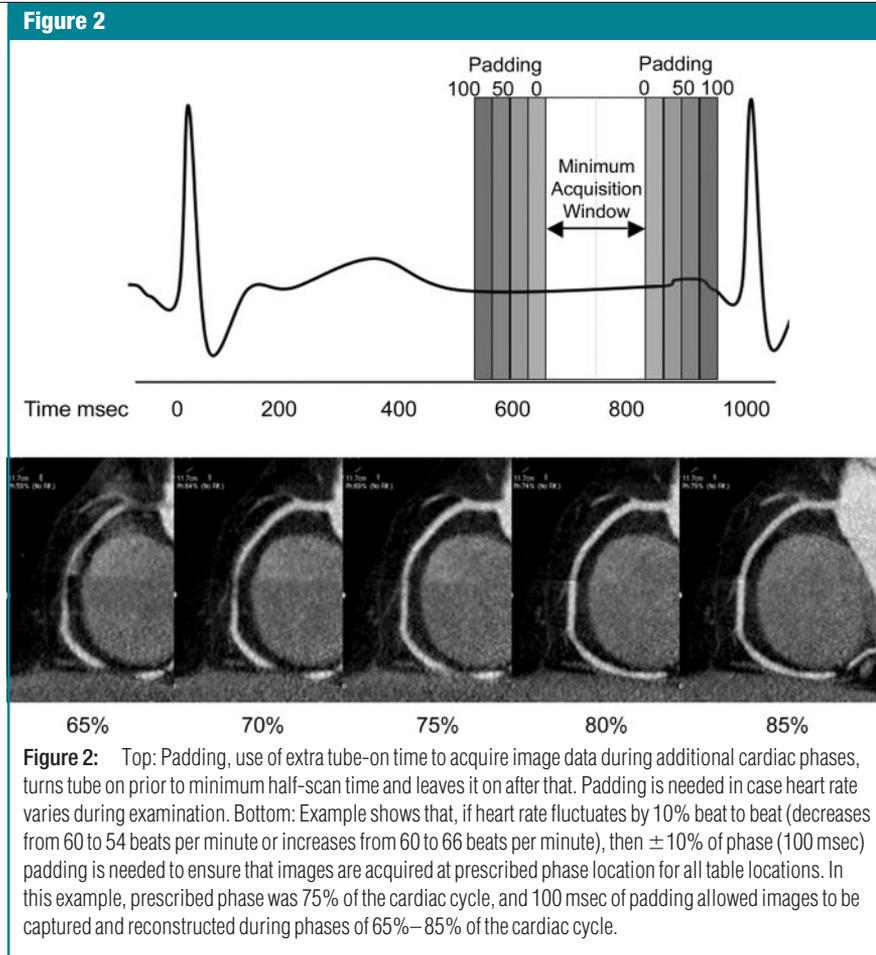


Figure 2: Top: Padding, use of extra tube-on-time to acquire image data during additional cardiac phases, turns tube on prior to minimum half-scan time and leaves it on after that. Padding is needed in case heart rate varies during examination. Bottom: Example shows that, if heart rate fluctuates by 10% beat to beat (decreases from 60 to 54 beats per minute or increases from 60 to 66 beats per minute), then $\pm 10\%$ of phase (100 msec) padding is needed to ensure that images are acquired at prescribed phase location for all table locations. In this example, prescribed phase was 75% of the cardiac cycle, and 100 msec of padding allowed images to be captured and reconstructed during phases of 65%–85% of the cardiac cycle.

did not assume equal variances. A *P* value of .05 was considered to indicate a significant difference.

For analysis of image quality score, we controlled for effects for reader and also for the correlated nature of the data because four arteries were evaluated in each subject. Two analyses with power calculations were performed. First, an ordinal regression was fit to the image quality scores to measure differences in image quality distributions among techniques, readers, and arteries. Second, artery assessability differences between the two techniques were analyzed by using a logistic regression on a binary outcome where an artery was considered assessable when the image quality score was more than 2.

We modeled the image quality

score by using a proportional odds logistic regression model (33) with main effects for the three readers, the two techniques, and the four arteries. The proportional odds model used here was specified as a marginal model (34) as follows:

$$\text{logit}[P(Y_a > j)] = \alpha_j + \beta_{1r} + \beta_{2t} + \beta_{3a}, \quad (1)$$

for artery *a*, *a* = 1, 2, 3, or 4; for reader *r*, *r* = 1, 2, or 3; and for technique *t*, *t* = 1 or 2. The left-hand side in Equation (1) is the logit of the probability *P* that the image quality score *Y_a* for artery *a* is assigned a score higher than *j*, where *j* ranges from one through four. The logit function, defined as $\text{logit}(x) = \log[x/(1 - x)]$,

transforms a probability into the logarithm of its odds. The transformation is *S* shaped: As the probability approaches zero, the logit goes to negative infinity; as the probability approaches one, the logit goes to positive infinity. All Greek letters on the right-hand side of Equation (1) are parameters to be estimated: The α_j values are the baseline log odds for each image quality score, and $\hat{\alpha}_{1r}$, $\hat{\alpha}_{2t}$, and $\hat{\alpha}_{3a[r]}$ are the log odds ratios (ORs) for the three independent predictors (reader, technique, and artery, respectively). We tested the proportional odds model assumption of a constant OR regardless of the choice of image quality cutoff value by applying separate binary logistic regressions of the form given in Equation (1), where *j* was varied, and the effects for reader, treatment, and artery were reestimated in each fit. No significant deviations were seen in the ORs from the multiple fits.

The generalized estimating equation method was used to estimate the effects for reader, technique, and artery of Equation (1), by using the `ordgee` function of the `geepack` library (version 1.0-11) in the R statistical package (version 2.4.1) (34,35). Clusters of size 4 were defined to model the correlation structure among the four artery measurements assigned to a subject by a reader.

In a second analysis, we quantified possible differences in the effect for technique according to artery through the addition of a technique-artery interaction to Equation (1) as follows:

$$\begin{aligned} \text{logit}[P(Y_a > j)] \\ = \alpha_j + \beta_{1r} + \beta_{2t} + \beta_{3a} + \beta_{4ta}. \end{aligned} \quad (2)$$

The interaction term β_{4ta} allows the effect of the technique on image quality to be different for the four arteries.

Analysis of artery assessability was performed by using a logistic regression (36), with assessability, defined as an image quality score greater than 3, as the outcome variable. Because of the very small number of arteries called unassessable, we were forced to collapse the data over artery by removing the

effect for artery from Equation (1). Main effects were included for reader and technique thus:

$$\text{logit}[P(Y > 2)] = \alpha + \beta_{1r} + \beta_{2t}, \quad (3)$$

for reader *r*, *r* = 1, 2, or 3, and for technique *t*, *t* = 1 or 2. The generalized estimating equation method was again used with clusters of size 4 to estimate the effects for reader and technique of Equation (3), by using the `geeglm` function of the `geepack` library in the R statistical package.

A power calculation was performed for both the image quality analysis and vessel assessability analysis. For the image quality analysis, we determined that at least 81 subjects in each technique group would be sufficient to detect a technique OR of 2.6 with 80% power while controlling the type I error rate at 5% in a two-sided hypothesis test (37). On the other hand, we determined that a very large sample size would be required to detect even large technique ORs for vessel assessability (>4) with 80% power because the assessability percentages for both groups were expected to be relatively high, greater than 90%–95%. Collecting such a large number of subjects was outside the scope of this project. Note that the methods given in an article by Walters (37) do not take into account the repeated-measures character of these data. For the purposes of the power calculations, we made the conservative assumption that only one artery was assessed per subject.

Results

Patients

Table 3 contains a summary of demographic information and the primary clinical indications for the examination. The age and sex distribution and clinical indications were similar for both groups. The heart rate during the scan and the use of β -adrenergic blocking agents were also similar in both groups (Table

2). The prevalence, percentage of patients with coronary stenoses depicted on the coronary CT angiograms, and severity of CAD, as measured by the coronary artery calcium score, were equivalent between the two groups (Table 3).

Scan Parameters

The mean scan time for the group undergoing CT with the RGH technique (5.8 seconds \pm 0.9) was greater than that for the PGT technique group (4.2 seconds \pm 0.9) ($P < .001$). The mean x-ray-on time for the PGT technique group was 0.9 seconds \pm 0.2 (range, 0.7–1.3 seconds). On average, a higher tube current was selected for the studies with the RGH technique (mean, 647 mA \pm 43; range, 348–771 mA) than for the studies with the PGT technique (mean, 507 mA \pm 132; range, 300–800 mA) ($P < .001$). The z-axis (cranial-caudal) coverage also was slightly greater in the patients in the RGH technique group (mean, 138 mm \pm 11; range, 97–166 mm) than for those in the PGT technique group (mean, 128 mm \pm 19; range, 105–175 mm) ($P < .001$). With the PGT technique, we found that 42% of patients could be imaged with three slabs, 56% of patients could be imaged with four slabs, and 2% of patients could be imaged with five slabs.

In one of the examinations with the RGH technique, performed in a 52-year-old woman (height, 5 ft 0 inches [150 cm]; weight, 200 lb [90 kg]; BMI, 39.0 kg/m²) with a stent in the right coronary artery and new chest pain, images of the distal right coronary artery were nondiagnostic because of poor image quality. At a later date, the examination was repeated by using the PGT technique, and findings were diagnostic, revealing a distal right coronary artery stenosis (Fig 3).

Radiation Dose

The mean effective radiation dose per examination in the RGH technique group was 18.4 mSv \pm 2.4 (range, 8.7–22.0 mSv), and the mean effective dose in the PGT technique group was 2.8 mSv \pm 1.3 (range, 0.75–6.7 mSv) ($P < .001$) (Fig 4). As stated previously, the

z-axis coverage for the examinations with the RGH technique was 7.8% longer than it was for those with the PGT technique. Correcting for this difference, the mean effective dose with the RGH technique can be reduced slightly to 17.1 mSv. This mean effective dose reduction represents a mean 83% reduction from the dose with the RGH technique to that with the PGT technique, and the difference was significant ($P < .001$).

The volume CT dose index represents the dose per volume and is not integrated over the prescribed z-axis length. The mean volume CT dose index was $67.6 \text{ mGy} \pm 7.3$ in the RGH technique group compared with that of $13.0 \text{ mGy} \pm 5.6$ in the PGT technique group ($P < .001$); this difference represented an 81% volume CT dose index reduction (Table 4). It should be noted that the radiation dose data presented here are for the diagnostic angiogram only. The examination also included scout scanograms, a low-dose transverse scout scan or a calcium-scoring scan, and a test-bolus scan. Together, these scans add an additional 1.2–2.3 mSv to the examination, and the dose of these additional images was similar for both RGH and PGT technique groups. There were seven subjects in the PGT technique group who received a radiation dose of 1.0 mSv or less; this subgroup had relatively low BMIs (mean, 21.5 kg/m^2 ; range, $14.5\text{--}25.7 \text{ kg/m}^2$) (Fig 5).

Image Quality

Analysis of the blinded reads revealed that image quality in the PGT technique group showed a small but consistent increase compared with the image quality in the RGH technique group (Table 5). By using a proportional odds logistic regression model, with the PGT technique, there was a significant improvement in image quality compared with that of the RGH technique. The estimated technique versus image quality OR of 2.8 (95% confidence interval: 1.7, 4.8) indicates that image quality scores with the PGT technique were significantly higher than the scores with the RGH technique. The technique versus image quality OR estimated here con-

trols for effects of reader and of artery and also accounts for the correlated nature of the scores assigned to different arteries in the same subject. No significant effects for reader were detected. We evaluated possible differences in the effect for technique according to artery. The conclusion was that, with the PGT technique, image quality significantly increased for all arteries, and there was no strong evidence of heterogeneity of the effect for technique among arteries.

Coronary Artery Assessability

We used the image quality scores to determine whether coronary artery segments were assessable and made the assumption that segments with scores

of 2 or less were nonassessable. By this definition, the percentage of nonassessable segments (image quality score, <3) was 1.4% for the PGT technique versus 2.1% for the RGH technique ($P = .83$). For the PGT technique, 1196 (98.6%) of 1213 coronary artery segments were assessable, and for the RGH technique, 1741 (97.9%) of 1778 coronary artery segments were assessable. By using binary logistic regression, no significant effect for technique was detected (OR, 1.1; 95% confidence interval: 0.04, 3.2). No effects for reader were detected. However, the power of this model to detect differences for technique or reader was very low because of the small number of nonassessable seg-

Table 3

Demographic Information, Primary Clinical Indication for Coronary CT Angiographic Examination, Calcium Score, and Examination Results for RGH and PGT Technique Groups

Clinical Data	RGH Technique	PGT Technique
Demographics		
Total no. of patients	82	121
Sex		
No. of men	44	71
No. of women	38	50
Age (y)*	55.6 ± 11.1 (29–84)	56.7 ± 13.3 (10–82)
BMI (kg/m^2)*	27.62 ± 5.4 (18.5–43.1)	28.32 ± 5.7 (14.6–47.6)
Percentage with primary clinical indication		
Chest pain	34.2	32.2
Abnormal results at nuclear myocardial perfusion imaging study	25.6	24.8
Abnormal results at exercise stress test	8.5	9.9
Shortness of breath, dyspnea on exertion	7.3	5.0
Elevated risk factors	6.1	7.4
Follow-up for CAD	4.9	4.1
Follow-up after stent placement	4.9	5.0
Other	8.5	11.6
Percentage with calcium score		
0	45.8	43.0
1–10	11.1	10.3
11–100	22.2	14.0
101–400	6.9	17.7
>400	13.9	15.0
Mean calcium score	183.1	227.9
Maximum calcium score	2085	3298
Percentage with CAD severity at coronary CT angiography		
No CAD	42.7	44.6
$\leq 50\%$ stenosis	43.9	36.4
>50% stenosis	13.5	19.0

* Data are the mean \pm standard deviation. Numbers in parentheses are ranges.

Figure 3

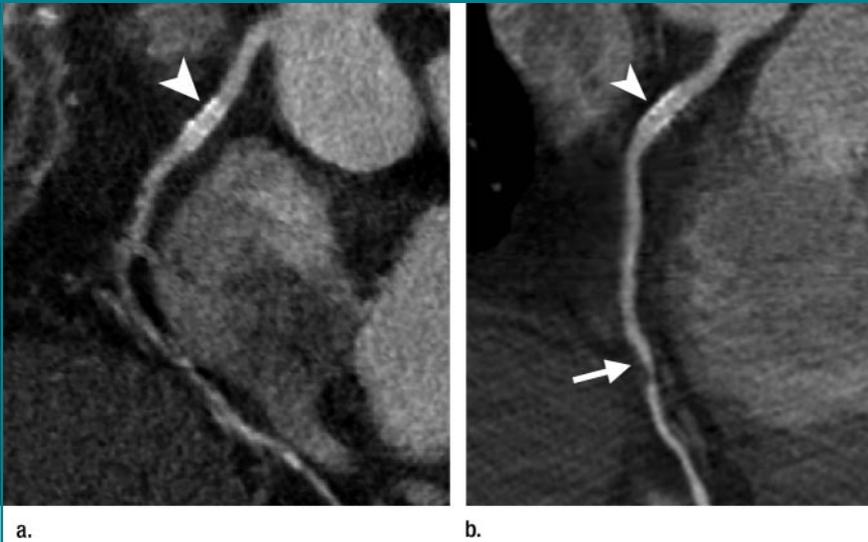


Figure 3: Curved multiplanar reformations of right coronary artery from coronary CT angiographic examinations with (a) RGH technique and (b) PGT technique in 52-year-old woman (height, 5 ft 0 inch [150 cm]; weight, 200 lb [90 kg]; BMI, 39.0 kg/m²) with right coronary artery stent and new chest pain. Initial RGH coronary CT angiographic scan depicted patent proximal right coronary artery stent (arrowhead) but was nondiagnostic because of poor image quality in distal right coronary artery. At repeat examination with PGT technique, scan was diagnostic and revealed distal right coronary artery stenosis (arrow). Radiation dose at PGT study was 3.9 mSv, which represented an 82% dose reduction from the 22-mSv dose at RGH examination.

ments. The percentage of segments with borderline image quality (score of 3) was 1.6% for the PGT technique versus 6.7% for the RGH technique.

Discussion

The high radiation dose of RGH coronary CT angiography is a concern for physicians (38). Efforts to reduce the high radiation dose with coronary CT angiography previously have focused on several approaches. Use of ECG-dependent dose modulation is the most effective method available clinically to reduce dose in RGH coronary CT angiographic examinations. This reduction can lead to a decrease in overall radiation dose of 20%–50%, depending on the heart rate (6,25,26). Other approaches have included decreasing the tube voltage; this decrease allows a reduction in effective dose, as the radiation dose varies as the tube voltage is increased by its value squared (6,26). Decreasing the tube voltage has the added benefit of allowing an increase in opacification of blood vessels caused by an increase in the photoelectric effect and a decrease in Compton scattering (38). Unfortunately, a reduction in tube voltage from 120 kV to either 100 or 80 kV allows a reduction in dose but also is associated with a decline in overall image quality (6,26).

PGT coronary CT angiography offers acquisition of images during a limited number of available reconstruction phases. This was initially a concern prior to having experience with the technique. Depending on the amount of padding used, the range of available cardiac phases for acquisition of images with the PGT technique can be from

Figure 4

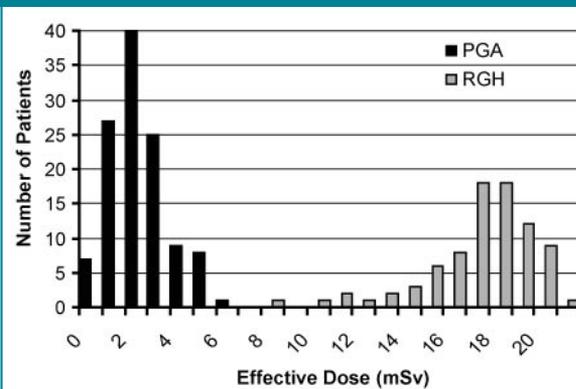


Figure 4: Distribution of effective radiation doses for RGH and PGT technique groups. Effective dose in RGH group was 8.7–22.0 mSv (mean, 18.4 mSv ± 2.4). Effective dose in PGT group was 0.75–6.7 mSv (mean, 2.8 mSv ± 1.3). This difference represents a mean 83% reduction from the dose with RGH technique to the dose with PGT technique; the difference was significant ($P < .001$).

Table 4

Radiation Doses for Diagnostic Angiographic Portion of Each Examination in the Study

Dose	RGH Technique				PGT Technique			
	Mean	SD	Minimum	Maximum	Mean	SD	Minimum	Maximum
Volume CT dose index (mGy)	67.6	7.3	30.9	96.4	13.0	5.6	4.0	37.4
Dose-length product (mGy · cm)	1082	140	511	1292	170	80	44	499
Effective dose (mSv)	18.4	2.4	8.7	22.0	2.8	1.4	0.8	6.7

Note.—SD = standard deviation.

10% to 50% of the cardiac cycle. With the RGH technique, images can be obtained during 100% of the cardiac cycle for analysis. In the past it was shown that end-systolic phase images may at times be more optimal for analysis of the right coronary artery; however, Leschka et al (39) and Hong et al (40) recently determined that only at heart rates greater than 85.5 beats per minute does the best reconstruction time shift to end systole. Despite limited available phases in PGT examinations, only 1.4% of coronary segments were nonassessable (image quality score of <3); this percentage was not significantly different as compared with the value of 2.1% for nonassessable segments with the RGH method.

The effective dose for the PGT group (mean, 2.84 mSv) was significantly lower than that for the RGH group (mean, 18.4 mSv) ($P < .001$). This difference represents an 83% reduction from the effective dose with the RGH technique to that with the PGT technique. Differences inherent in the two techniques, low-pitch helical for the RGH technique and transverse with minimal overlap for the PGT technique, account for most of the effective dose differences. "Overbeaming," extra exposures at the start and end of a helical acquisition, of the RGH technique also contributes significantly to the overall dose increase. The remainder of the difference is likely caused by some variation in other parameters common to both methods, including tube current, and z-axis coverage. Although the tube voltage was held at 120 kV for all patients, on average a higher tube current was used for the RGH group subjects (mean, 647.6 mA; range, 348–771 mA) than for the PGT group subjects (mean, 507.3 mA; range, 300–800 mA). In addition, slightly greater anatomic coverage was prescribed for the RGH group subjects than for the PGT group subjects, also contributing to higher effective dose.

There were seven subjects in the PGT group who received a radiation dose of 1.0 mSv or less. We believe that these are the lowest reported effective doses for coronary CT angiography. Abada

Figure 5

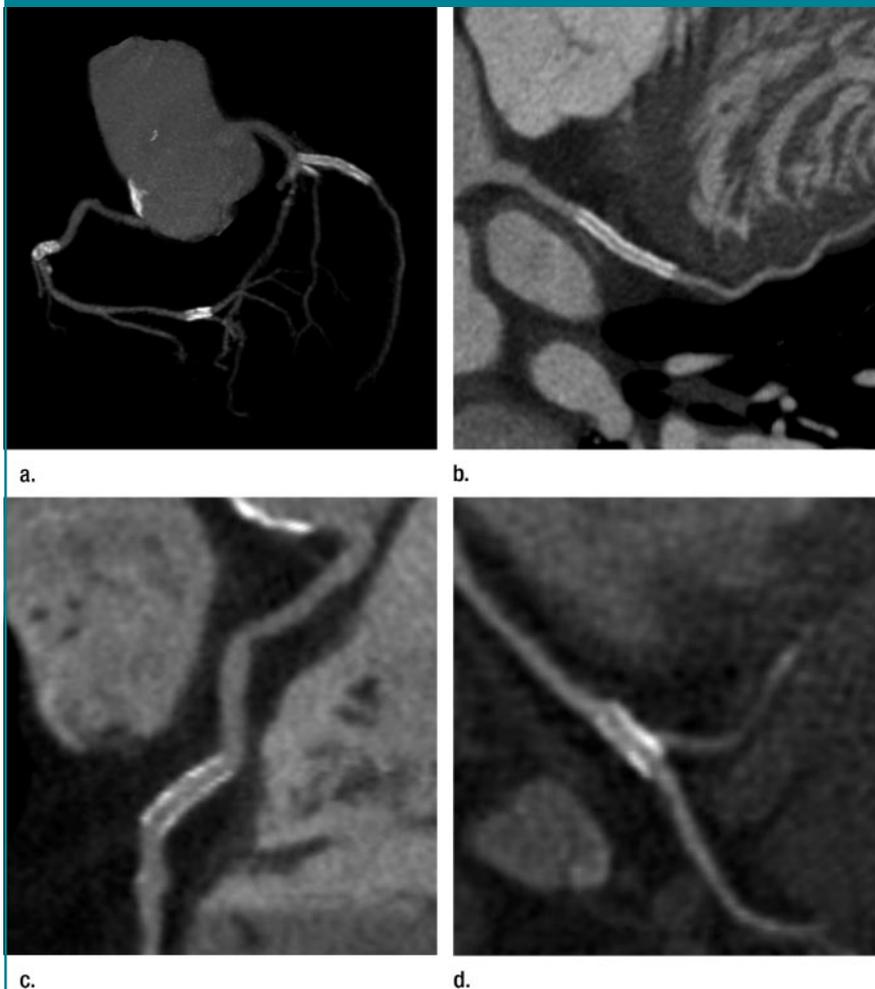


Figure 5: PGT coronary CT angiograms with dose less than 1-mSv in 73-year-old man (5 ft 5 inch [162.7 cm]; 133 lb [59.8 kg]; BMI, 22.3 kg/m²) with long history of CAD, three coronary stents, and possible inferior wall ischemia revealed with dual-isotope myocardial perfusion examination. **(a)** Maximum intensity projection depicts position of all three stents. **(b–d)** Curved planar reformatted images. **(b)** Patent 2.5-mm-diameter 26.0-mm-long stent in the first obtuse marginal coronary artery. **(c)** Patent 3.0-mm-diameter 13.0-mm-long stent in middle of right coronary artery. **(d)** Patent 3.0-mm-diameter 9.0-mm-long stent in distal right coronary artery. No significant stenoses were depicted.

et al (26) reported relatively low effective doses of approximately 2 mSv by using a modified RGH technique in a group of 11 slim patients (<60 kg) in which the tube voltage was reduced to 80 kV, ECG modulation was used, and the tube current was 520 mA.

Physicians performing CT in general adhere to the as low as reasonably achievable, or ALARA, principle. However, even with strict adherence to this principle, the radiation dose of coronary CT angiography remains relatively

high, and the long-term risk to the patient of developing radiation-induced cancer must be considered (41). Although all patients benefit from decreasing the effective dose of coronary CT angiographic examinations, we believe that a decrease is especially promising for premenopausal women (because of the direct breast exposure) and middle-aged and younger patients because of the longer lag time that exists for a cancer to develop. Additionally, patients who might in the future undergo re-

peated coronary CT angiographic studies, such as those with coronary stents, bypass grafts, complex congenital anomalies, or known coronary stenoses, may also benefit because of the lower cumulative dose.

Recently, the National Research Council's Committee on the Biological Effects of Ionizing Radiation released their seventh report on the health effects of exposure to low-dose ionizing radiation (42). The committee calculated that a dose of 10 mSv would cause one in 1000 lifetime cancers but acknowledged that this calculation could be off by a factor of two or three (16). The International Commission on Radiological Protection had previously estimated that a dose of 10 mSv would cause one in 2000 lifetime cancers (43). On the basis of these estimates, helical coronary CT angiography with an effective dose of 15 mSv has a range of risk of inducing a fatal cancer of one in 677 (Committee on the Biological Effects of Ionizing Radiation, seventh report [42]) to one in 1333 (International Commission on Radiological Protection [43]). Coronary CT angiography performed with the PGT technique and an estimated dose of 2.8 mSv would yield a theoretical risk of one in 3571 (Committee on Biological Effects of Ionizing Radiation, seventh report [42]) to one in 7143 (International Commission on Radiological Protection [43]).

It may be useful to put the coronary CT angiographic effective doses in context with other cardiac diagnostic tests.

Conventional coronary angiography has an approximate dose of 5.6 mSv (15). The effective dose for a rest-stress myocardial single photon emission CT scan obtained by using technetium 99m (^{99m}Tc) is 8–17.5 mSv (16,44). The dose for a thallium 201 (^{201}Tl) stress and reinjection scan is 18–25.1 mSv, and a dual-isotope technique study performed by using ^{201}Tl and ^{99m}Tc has an effective dose of 27.3 mSv (16,44). The long-term risk of developing a radiation-induced cancer from any single cardiac imaging study is relatively small. However, patients with CAD undergo multiple examinations over their lifetimes. Thus, the risks are likely to be substantially larger. Because PGT coronary CT angiography represents a substantial dose savings as compared with any of the other noninvasive cardiac studies with radiation, widespread use in lieu of these other examinations will likely yield a widespread benefit in relation to reduced overall risk.

We have shown that the quality of images from PGT examinations was significantly better than that of images from RGH examinations. This can be explained by several reasons. First, the PGT examinations had a shorter scan time (4.2 seconds for PGT vs 5.7 seconds for RGH), allowing less time for ectopy or heart rate acceleration or deceleration to occur, all of which can adversely affect image quality. In addition, with the PGT technique, the table remains stationary during the data acquisition, unlike with the RGH technique in

which the patient is constantly moving during the scan. With the PGT technique, one can also take full advantage of the predictive gating capability allowed by the stationary table; variation in the heart rate will simply translate to a delayed or earlier data acquisition and reconstruction. With the PGT technique, a newer gated complementary reconstruction algorithm that further improves image quality is used (27). Results of a recent study with a phantom in which PGT and RGH techniques were compared revealed in-plane resolution to be 8% higher and section sensitivity in the z-axis to be 6% better for the PGT technique (45).

There were limitations to our study. Ours was a retrospective analysis of clinical cases. Therefore, many parameters were not strictly controlled, and bias could have been introduced. In the RGH technique group, we identified a higher tube current, which contributed negatively to overall dose but likely helped, or at least did not hinder, overall image quality. There was also a slightly greater amount of z-axis coverage in the RGH technique group, which also increased its effective dose. The current PGT implementation itself has inherent limitations. With its current revision, heart rates are limited to less than 70 beats per minute and administration of β -adrenergic blocking agents is required in most patients because of the lack of multisector reconstruction capability. Although image quality is usually excellent at 60–70 beats per minute, we use β -adrenergic blocking agents in patients in this group to minimize or, hopefully, eliminate heart rate accelerations (or decelerations) during data acquisition because they can contribute negatively to image quality. We found that the limitation of 70 beats per minute allows us to image approximately 92% of clinical patients with the newer technique.

Because of the narrow range of available reconstruction windows, neither global nor regional function can be determined with the PGT technique, although in theory expanded acquisition windows with the PGT technique could offer such capability at the cost of a

Table 5

Results of Image Quality Evaluation

Artery	PGT Technique	RGH Technique	Difference between Techniques*
Left main coronary	4.911	4.654	0.257
Left anterior descending	4.817	4.492	0.325
Circumflex	4.789	4.472	0.317
Right coronary	4.652	4.443	0.209
All	4.791	4.514	0.277

Note.—Image quality was evaluated and classified by three independent readers by using a previously described (32) five-point scale. In this scale, a score of 5 is the highest possible score, and a score of 1 was assigned for an image that could not be evaluated. Analysis of the three blinded reads revealed that the PGT technique was generally preferred for all four arteries, with improvement ranging from 0.209 in the right coronary artery to 0.325 in the left anterior descending artery. Considering that most image quality scores in the entire experiment were in the two highest categories, this is a fairly large increase in average score.

* $P < .001$, all values.

higher dose. In our clinical practice, most patients presenting for coronary CT angiography have already had either an echocardiogram or a nuclear myocardial perfusion examination prior to the coronary CT angiographic examination, and cardiac function usually is not requested or analyzed with CT. Even in cases in which cardiac function is desired, the additional 10–15 mSv required to change from PGT to a helical technique may not be the optimal approach, as other noninvasive methods for determining function are available with no radiation dose.

In summary, we have shown here that coronary CT angiography performed with a PGT technique, compared with an RGH technique, provides a substantial (>80%) effective radiation dose reduction and significantly improves image quality. We believe this technique has great promise to become a commonly used method for coronary CT angiography.

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