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Whole-Chest 64-MDCT of Emergency Department Patients with Nonspecific Chest Pain: Radiation Dose and Coronary Artery Image Quality with Prospective ECG Triggering Versus Retrospective ECG Gating

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Abstract

Objective—The purpose of this study was to compare the patient radiation dose and coronary artery image quality of long-z-axis whole-chest 64-MDCT performed with retrospective ECG gating with those of CT performed with prospective ECG triggering in the evaluation of emergency department patients with nonspecific chest pain.

Subjects and Methods—Consecutively registered emergency department patients with nonspecific low-to-moderate-risk chest pain underwent whole-chest CT with retrospective gating ($n = 41$) or prospective triggering ($n = 31$). Effective patient radiation doses were estimated and compared by use of unpaired Student's t tests. Two reviewers independently scored the quality of images of the coronary arteries, and the scores were compared by use of ordinal logistic regression.

Results—Age, heart rate, body mass index, and z-axis coverage were not statistically different between the two groups. For retrospective gating, the mean effective radiation dose was 31.8 ± 5.1 mSv; for prospective triggering, the mean effective radiation dose was 9.2 ± 2.2 mSv (prospective triggering 71% lower, $p < 0.001$). Two of 512 segments imaged with retrospective gating were nonevaluable (0.4%), and two of 394 segments imaged with prospective triggering were nonevaluable (0.5%). Prospectively triggered images were 2.2 (95% CI, 1.1–4.5) times as likely as retrospectively gated images to receive a high image quality score for each segment after adjustment for segment differences ($p < 0.05$).

Conclusion—For long-z-axis whole-chest 64-MDCT of emergency department patients with nonspecific chest pain, use of prospective ECG triggering may result in substantially lower patient radiation doses and better coronary artery image quality than is achieved with retrospective ECG gating.

Keywords

cardiac CT; gating technique; image quality; radiation dose

Nonspecific chest pain in emergency department patients suggests several diagnoses, among them coronary artery disease, acute aortic syndrome, and pulmonary embolus. Although some of these patients may be in unstable condition or acutely ill and need immediate therapy, many patients with nonspecific chest pain may be evaluated less urgently. 64-MDCT of the whole chest with retrospective ECG gating has been reported to have a high negative predictive value in the differentiation of the several causes of chest pain [1–8]. However, retrospective gating delivers a high patient radiation dose because the low pitch values (0.20–0.26) result in overscanning of tissue and because the beam is on for 100% of the R-R interval. Even with intensity modulation, the patient dose for whole-chest CT with retrospective gating can be as high as 36 mSv (Hausleiter J et al., presented at the 2008 scientific session of the American College of Cardiology) [9]. This high patient radiation dose may restrict the use of whole-chest gated CT in the emergency department.

CT with prospective ECG triggering is a step-and-shoot technique with a beam-on time of approximately 26% of the R-R interval and little overscanning [10]. With the table stationary, the brief beam-on time exposes 4 cm along the z-axis in the diastolic portion of an R-R interval. During the subsequent R-R interval and with the beam off, the table moves 4 cm to the position for the next exposure during the next heartbeat. For short-z-axis cardiac CT, prospective triggering reduces the effective radiation dose 77–83% with coronary artery image quality similar to or better than that of retrospective gating [11–13].

For long-z-axis whole-chest ECG-gated CT, the greatest technical challenge is maintaining image quality in the small fast-moving coronary arteries while CT parameters and injection technique are altered to achieve good opacification in the pulmonary arteries and thoracic aorta. We hypothesized that prospective ECG triggering could result in substantial radiation dose reduction for long-z-axis whole-chest CT with maintenance of good coronary artery image quality similar to that of short-z-axis cardiac CT. Our purpose was to compare the patient radiation dose and coronary artery image quality of long-z-axis whole-chest CT performed with retrospective ECG gating with the patient dose and coronary artery image quality of CT performed with prospective ECG triggering in emergency department patients with nonspecific chest pain.

Subjects and Methods

This prospective HIPAA-compliant study was approved by the university institutional review board. Written informed consent was obtained from each patient by a trained and experienced research associate who recruited patients in the emergency department between the hours of 7 am and 6 pm Monday through Friday.

Patients

Patients judged by emergency department physicians to be in unstable condition or acutely ill and needing immediate therapy were not considered for enrollment. All qualifying patients had nonspecific chest pain and a low or moderate thrombolysis in myocardial infarction (TIMI) risk score of 0–4 [14–17]. Each patient consented to whole-chest ECG-gated CT in addition to the standard-of-care evaluation. Clinical exclusion criteria for cardiac CT included severe allergy to iodine-containing contrast material, history of compromised renal function (calculated glomerular filtration rate < 40 mL/min/1.73 m² body surface area), pregnancy, nonsinus rhythm, severe respiratory or cardiac failure, female

sex and younger than 45 years, male sex and younger than 30 years, and body mass index (weight in kilograms divided by height squared in meters) greater than 40. Patients also were excluded if they had a positive initial cardiac enzyme result, new ischemic ECG changes, TIMI risk score greater than 4, known cardiac disease, or inability to attain a heart rate less than 75 beats/min with the use of β -blockers (two patients were not enrolled because of inability to decrease the heart rate to less than 75 beats/min with β -blockers). Patients who met any of the exclusion criteria at screening were not approached or enrolled in the study. Between September 2006 and May 2008 we enrolled 74 consecutively registered patients who met these criteria. Initially only retrospective gating was available on our CT scanner, so the first group of 42 patients enrolled underwent scanning with retrospective ECG gating. After prospective triggering became available on our CT scanner, the subsequent group of 32 patients underwent scanning with prospective ECG triggering. Two patients were excluded after enrollment because of examination failure: one from the retrospective-gating group owing to computer error that resulted in loss of images and one from the prospective-triggering group owing to failure of IV access. The final study population thus included 41 patients in the retrospective-gating group and 31 patients in the prospective-triggering group.

CT Technique

Patients who arrived in the emergency department with a heart rate greater than 55 beats/min received 50–100 mg of an oral β -blocker 45–60 minutes before the CT examination ($n = 60$) (metoprolol tartrate, Lopressor, Novartis) or received 5–15 mg IV of metoprolol ($n = 6$). Six patients did not receive β -blockers because of low heart rate on arrival in the emergency department. All patients also received 0.4 mg of sublingual nitroglycerine spray (Nitrolingual Pumpspray, Sciele Pharma) administered 4–8 minutes before cardiac CT unless this medication was contraindicated by allergy, hypotension, or use of a phosphodiesterase inhibitor. CT examinations were performed with a 64-MDCT scanner (LightSpeed VCT XT, GE Healthcare). Circulation time from the antecubital fossa to the aortic root was determined in each case with a timed bolus of 20 mL of iodixanol (Visipaque 320, GE Healthcare). A dual-head power injector (Stellant D, Medrad) was used to administer a long three-phase bolus tailored to opacify the three target arterial structures (pulmonary arteries, coronary arteries, thoracic aorta) at the same time during the scanning interval: 70 mL of iodixanol followed by 50 mL of a 70/30% blend of iodixanol and saline solution followed by 50 mL of saline solution, all at 5 mL/s [18–20].

CT examinations were performed at full inspiration in a craniocaudal direction from the thoracic inlet to a position immediately inferior to the heart. Detector collimation was 64×0.625 mm, and the gantry rotation time was 0.35 second. Tube voltage was adjusted to body weight: 100 kVp for patients weighing less than 170 pounds (77.1 kg) and 120 kVp for patients weighing more than 170 pounds. All images had a reconstruction slice thickness of 0.625 mm and an interval of 0.625 mm with a small or medium cardiac field of view (24 cm). Images were reconstructed with a soft-tissue algorithm (Standard, GE Healthcare).

ECG tube current modulation was used for CT examinations performed with retrospective gating. For patients weighing less than 170 pounds, the tube current was set at 600 mA during 60–80% of the R-R interval and 200 mA during the rest of the R-R interval. For patients weighing 170 pounds (77.1 kg) or more, the tube current was set at 790 mA during 60–80% of the R-R interval and 400 mA during the rest of the R-R interval [11, 21]. Scanning was accomplished in 6–8 heartbeats, requiring a breath-hold of 10–14 seconds. Among patients, pitch varied between 0.20 and 0.24 as selected by the scanner depending on initial heart rate, but it remained constant during scanning.

Images were first constructed at 75% of the R-R interval and then reconstructed at 0–90% of the R-R interval in 10% increments through the region of the heart to include images from both systole and diastole. Reconstruction increments of 5% for the entire R-R interval exceeded the image capacity of the scanner computer, so increments of 10% were used from 0–90% except for the addition of 75% in order to have 5% increments through the critical part of diastole (70%, 75%, and 80%).

For CT examinations performed with prospective triggering (Snapshot Pulse, GE Healthcare), the tube current was set at 400 mA for patients weighing less than 170 pounds (77.1 kg) and at 500 mA for patients weighing 170 pounds or more [22, 23]. Scanning used 6–10 of the 4-cm slabs, requiring 10–16 heartbeats and a typical breath-hold of 12–18 seconds (scanning of a 4-cm slab every other heartbeat with table motion during the intervening heartbeats). Scan beam-on time per 4-cm slab was 265 milliseconds (including 100 milliseconds of temporal padding) centered at 70% of the R-R interval and covering approximately 60–80% of it. Images were reconstructed from 60% to 80% of the R-R interval in 5% increments, which was possible because of the shorter proportion of the R-R interval imaged with prospective triggering.

Postprocessing

Images for all cardiac CT examinations were sent to a dedicated 3D workstation (Advantage Windows 4.4, GE Healthcare). Image sets available on the workstation included axial reconstructed images sent from the CT scanner, multiplanar reformations, curved planar reformations rotated through 360° along the course of each coronary artery and major side branches, and thin-slab maximum intensity projections generated on the workstation. Curved planar images of the coronary arteries also were displayed.

Coronary Artery Image Quality Analysis

All CT images were reviewed for coronary artery image quality by two board-certified cardiac imagers: one radiologist with 25 years of chest CT experience and 4 years of cardiac CT experience and one cardiologist with 5 years of cardiac imaging experience and 4 years of cardiac CT experience. The reviewers were not informed about patient clinical information and were blinded to patient identity. The two reviewers evaluated images independently, reading at different times. Segments of the three main coronary arteries and their major side branches down to a minimal diameter of 1.5 mm were defined according to the 15-segment American Heart Association model [24], which was modified with the addition of segment 16 for the distal half of the circumflex coronary artery, segment 17 for a ramus intermedius when present, and segments 18 and 19 for additional obtuse marginal branches when present.

CT images obtained with retrospective gating and those obtained with prospective triggering were randomly presented during each reading session. The reviewers examined retrospectively gated images reconstructed at 0–90% of the R-R interval in 10% increments plus the original 75% reconstruction increment and scored each coronary artery segment for image quality using the reconstructed percentage judged best for that segment. The full range of R-R reconstruction increments was made available to the reviewers in the scoring of retrospectively gated images to include situations in which late systole produced the best image quality (20–40% of the R-R interval). This approach presented to the reviewers the full capability of the retrospective gating technique. The reviewers examined prospectively triggered images reconstructed at 60–80% of the R-R interval in 5% increments and scored each coronary artery segment for image quality using the reconstructed percentage judged best for that segment. The number of reconstructed increments available to the reviewers for

prospectively triggered images was limited by the shorter duration of the beam-on time during diastole only.

Coronary artery segment image quality was scored on a 4-point Likert scale similar to scales used by previous authors investigating coronary artery image quality in cardiac CT [12, 25–27]. Nonevaluable segments were scored 4, lack of vessel wall definition due to marked motion artifact, poor vessel opacification, prominent structural discontinuity, or blurring related to high image noise that resulted in absence of diagnostic information. Evaluable segments were scored 3, some motion artifact or noise-related blurring, fair vessel opacification, or minimal structural discontinuity; 2, minor motion artifact or noise-related blurring, good vessel opacification, and no structural discontinuity; or 1, absence of motion artifact and noise-related blurring, excellent vessel opacification, and no structural discontinuity (Figs. 1–3). Image quality degradation caused by any premature beats or coronary artery calcification was included in this scoring. Segments smaller than 1.5 mm were not scored.

For any segment image quality score, if the reviewers differed by only one image quality score after their separate reading sessions, the higher numeric score (lower quality) was used for statistical analysis. If the reviewers differed by more than one image quality score after their separate reading sessions, the discrepancy was resolved at a third session with the reviewers reading together at the same time to reach consensus.

Radiation Dose

The dose–length product displayed by the CT scanner was recorded by one author for each whole-chest CT examination, including scout views, aortic root localization run, timed-dose run, and the diagnostic run. The effective dose in millisieverts was calculated by multiplication of the dose–length product by the conversion coefficient for the chest, 0.017 [28].

Statistical Analysis

The statistical software packages used for data analysis were Stata/MP 10.0 (StataCorp) and SPSS 16.0 for Windows (SPSS). Comparison of patient data for the two groups was performed with a Student's *t* test for continuous covariates, such as age, and a chi-square test for categorical variables, such as sex. Agreement of image quality scores was assessed with kappa statistics with ranges of fair (0.21–0.40), moderate (0.41–0.60), good (0.61–0.80), and very good (0.81–1.00) [29]. Because the difference between image quality scores is not quantifiable, proportional odds ordinal logistic regression was used to compare the resolved scores of individual segments within each patient in each group [30]. Estimates of difference by gating type were adjusted for differences in the image quality of each segment number. Empirically corrected standard error was used to account for correlation between segments on the same image [31].

Results

Characteristics of Groups

There was no statistical difference between the two groups in heart rate, sex, age, body mass index, or percentage of patients weighing more than 170 pounds (77.1 kg) (Table 1). There was no statistical difference between the two groups in TIMI risk score ($p = 0.11$; 95% CI, 0.85–4.85).

Radiation Dose

The mean *z*-axis length for retrospectively gated examinations was 22.3 ± 3.2 (SD) cm (range, 16.2–25.4 cm) and was not statistically different from the mean *z*-axis length for prospectively triggered examinations, which was 21.9 ± 3.1 cm (range, 17.4–24.4) ($p = 0.41$). The mean patient radiation dose for retrospectively gated examinations was 31.8 ± 5.1 mSv (range, 27.3–40.5 mSv). For prospectively triggered examinations, the mean dose was 9.2 ± 2.2 mSv (range, 7.2–11.6 mSv) ($p < 0.001$). The mean patient radiation dose was 71% lower for prospective triggering than for retrospective gating.

Quality Scores

Agreement between the reviewers for segment image quality scores was classified as very good ($\kappa = 0.88$) [29]. Scoring coronary artery segment image quality readings separately, the reviewers differed more than one score on 52 segments and disagreed whether a segment was large enough to score on 59 segments. Both of these categories of disagreement were resolved in the consensus reading.

There were 906 coronary artery segments larger than 1.5 mm. Of the 512 coronary artery segments imaged with retrospective gating, two were nonevaluable (score 4). Of the 394 coronary artery segments imaged with prospective triggering, two also were nonevaluable (score 4) (Table 2). The difference in segment numbers per patient between the two groups was due to variations in coronary artery anatomy or small-vessel diameter (< 1.5 mm). For all patients, individual segment images obtained with prospective triggering were 2.2 times as likely as images of the corresponding segment obtained with retrospective gating to have a higher quality score (95% CI, 1.1–4.5 times; $p < 0.05$).

Discussion

In emergency department patients, non-specific chest pain suggests several diagnoses that can be evaluated with long-*z*-axis whole-chest ECG-gated CT. These long-*z*-axis gated examinations may uniquely benefit from the dose reduction of prospective triggering. With a reduced dose, maintaining image quality in the small, fast-moving coronary arteries is important.

Previous authors have reported that retrospectively ECG-gated CT of the whole chest as a single examination can achieve successful simultaneous opacification of the coronary arteries, pulmonary arteries, and thoracic aorta [18]. Even with the use of intensity modulation, the radiation dose of such long-*z*-axis gated CT is in the range of 15–36 mSv [9]. This dose is high in part because retrospective gating entails the use of low pitch values (0.20–0.26), resulting in helical overscanning of tissue, and because the beam is on throughout the R-R cycle.

In prospectively triggered cardiac 64-MDCT, the ECG signal is monitored in real time and a brief diastolic beam-on portion of the next R-R interval is prospectively selected through analysis of several beats before the actual scan [10]. To the required beam-on time of 165 milliseconds, up to an additional 200 milliseconds of padding may be added so that images can be adaptively reconstructed earlier or later than anticipated in the event of small heart rate irregularities. With 100 milliseconds of padding added, the resultant beam-on time of 265 milliseconds per R-R interval allows image reconstruction between 60% and 80% of the R-R interval, usually in 5% increments. In addition, prospective triggering is a step-and-shoot technique, meaning there is no table motion during the beam-on time. Rather, the table moves the length of the detector every other cardiac beat while the beam is off. During this table motion, both acceleration and deceleration are steady to minimize body motion independently of the table. In addition, the approximately 500 milliseconds of pause

between the end of the table motion and the next beam-on period dampens any residual body motion. Absence of table motion during the brief beam-on time may have a beneficial effect on image quality. In addition, prospective triggering is a predictive gating technique, which may be able to handle small changes in heart rate through variable timing of reconstruction.

In 2006, Hsieh et al. [10] described a step-and-shoot prospectively triggered acquisition protocol for coronary artery imaging in which a complementary reconstruction algorithm was used to overcome challenges with cone beam geometry [10]. They postulated that the reduction in patient radiation dose compared with standard retrospective gating would be at least 50% without reduction in image quality. In subsequent clinical investigations, investigators have documented substantial dose reduction with prospective triggering for short-z-axis cardiac CT compared with retrospective gating while attaining equal or slightly superior coronary artery image quality. Earls et al. [11] found an 83% dose reduction for cardiac CT with prospective triggering and better image quality scores than with unmatched retrospective gating. Shuman et al. [12] reported 77% dose reduction for prospective ECG-triggered cardiac CT with equivalent coronary artery image quality scores in patients matched for clinical characteristics.

In this investigation, we looked at both dose reduction and coronary artery image quality of long-z-axis whole-chest ECG-gated CT. We found 71% dose reduction and better coronary artery image quality with prospective triggering than with retrospective gating. We speculate that substantially lower patient dose with better image quality resulting from the use of prospective triggering may improve the utility of whole-chest ECG-gated CT in emergency department patients with nonspecific chest pain. In this series, acutely ill patients and those who emergency department physicians believed needed immediate therapy were not enrolled.

There are two important limitations of whole-chest prospective ECG triggering. First, the beam-off table motion of 4 cm takes approximately 1 second during alternate heartbeats. This table motion time limits single-sector prospective triggering to patients with heart rates less than 75 beats/min, as described by Hirai et al. [21]. Second, with prospective triggering, cardiac images are acquired during only a small portion of the R-R interval, so functional information about the motion of cardiac valves, wall motion, wall thickening, and ejection fraction is not available. There are some emergency department chest pain patients for whom cardiac functional information may be diagnostically useful, particularly those who have a history of cardiac disease. For such patients, retrospective gating may be preferable.

Our study had several important limitations. First, scoring of image quality on a Likert scale is by nature a subjective process. However, our very good kappa values for interobserver agreement in coronary artery segment image quality suggest reproducibility. Second, the image quality scoring scale we used was arbitrary. However, the Likert scale used in this investigation is derived from four other similar scales used effectively by previous investigators [12, 25–27].

A third limitation was that although the reviewers were not informed at the time of scoring about the ECG-gating technique for each examination, the R-R interval reconstruction percentages were different for each technique, precluding complete blinding. The range of reconstruction for prospectively triggered examinations was limited to 60–80% by the shorter beam-on time. We could have chosen to present retrospectively gated images from that same limited R-R percentage range, but we believed that such an approach would have unfairly compromised the retrospective gating technique by excluding the systolic phase images, one of the key comparative strengths of that technique. During the important 70–80% range, 5% increments were presented for each technique because retrospectively gated

images were first constructed at 75% and then reconstructed at 10% intervals, including 70% and 80%.

A fourth limitation was that we did not look at pulmonary arterial or aortic enhancement resulting from the injection protocol in this investigation, but we are addressing this question in a separate report. We and others have reported success with simultaneous diagnostic-level opacification of the coronary arteries, pulmonary arteries, and thoracic aorta using similar injection protocols [18–20]. We reasoned that the greatest technical challenge for a lower-dose ECG-triggered CT technique was achieving good image quality in the small, fast moving coronary arteries while scanning the whole chest. Fifth, our weight-based method for selecting tube current and peak kilovoltage for both types of gating was based on our experience and on previously described techniques with CT equipment similar to that referenced. Other methods of selecting those scan parameters might have produced different conclusions. Finally, our results must be confirmed in a prospective randomized study that includes other patient samples from multiple institutions.

We conclude that for whole-chest 64-MDCT of emergency department patients with nonspecific chest pain, prospective ECG triggering may result in substantially lower patient radiation dose and better coronary artery image quality than does retrospective ECG gating. The benefits of prospective triggering of whole-chest CT must be weighed against two current reported limitations: Imaging at heart rates greater than 75 beats/min is not recommended, and information about cardiac function is not produced [21].

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Fig. 1. 47-year-old man with nonspecific chest pains. Prospectively triggered CT image of right coronary artery with image quality score of 3: motion artifact or noise-related blurring, fair vessel opacification, minimal structural discontinuity.

Fig. 2. 54-year-old man with nonspecific chest pains. Prospectively triggered CT image of right coronary artery with image quality score of 2: minor motion artifact or noise-related blurring, good vessel opacification, and no structural discontinuity.

Fig. 3. 49-year-old man with nonspecific chest pains. Prospectively triggered CT image of right coronary artery with image quality score of 1: absence of motion artifact and noise-related blurring, excellent vessel opacification, and no structural discontinuity.

Table 1
Patient Characteristics

Characteristic	Retrospective Gating (<i>n</i> = 41)	Prospective Triggering (<i>n</i> = 31)	<i>p</i>
Heart rate (beats/min)	61 ± 5	59 ± 6	0.13 ^a
Age (y)	54 ± 8	55 ± 8	0.68 ^a
Male sex (<i>n</i>)	22 (54)	18 (58)	0.71 ^b
Body mass index	29 ± 5	28 ± 5	0.29 ^a
Body weight > 170 lb (77.1 kg) (<i>n</i>)	27 (66)	21 (68)	0.91 ^b

Note—Data are mean ± SD or number of patients with percentages in parentheses.

^aTwo-tailed Student's *t* test used for comparisons of groups.

^bPearson's chi-square test used for comparisons of groups.

Table 2
Image Quality Scores

Coronary Segment Image Score	No. of Segments	
	Retrospective Gating (<i>n</i> = 512)	Prospective Triggering (<i>n</i> = 394)
1	264 (52)	273 (69)
2	174 (34)	98 (25)
3	72 (14)	21 (5)
4	2 (0.4)	2 (0.5)

Note—Prospectively triggered images were 2.2 (95% CI, 1.1–4.5) times as retrospectively gated images to receive a high image quality score ($p < 0.05$). Values in parentheses are percentages.