320-detector CT coronary angiography with prospective and retrospective electrocardiogram gating in a single heartbeat: comparison of image quality and radiation dose

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Objectives: To compare the image quality, radiation dose and diagnostic accuracy of 320-detector CT coronary angiography with prospective and retrospective electrocardiogram (ECG) gating in a single heartbeat.

Methods: Two independent reviewers separately scored image quality of coronary artery segment for 480 cardiac CT studies in a prospective group and a retrospective group (240 patients with a heart rate <65 beats per minute in each group). The two groups matched well for clinical characteristics and CT parameters. There was good agreement for image quality scores of coronary artery segment between the independent reviewers ($\kappa=0.73$). Of the 7023 coronary artery segments, the image quality scores of the prospective group and retrospective group were not significantly different ($p>0.05$). The mean radiation dose was 10.0 ± 3.5 mSv (range 6.2–21.6 mSv) for prospective ECG gating at 65–85% of R–R interval (the interval between the R-wave of one heartbeat to the R-wave of the next). The mean radiation dose for retrospective ECG-triggered modulated scans was 23.2 ± 3.4 mSv (range 17–27.4 mSv). The mean radiation dose was 57% lower for prospective gating than for retrospective gating ($p<0.01$).

Results: Compared with coronary angiography, the results for prospective vs retrospective ECG gating were 92% vs 90% for sensitivity ($p=0.23$), 89% vs 91% for specificity ($p=0.19$), 90% vs 93% for positive predictive value ($p=0.25$) and 92% vs 95% for negative predictive value ($p=0.21$) for lesions with $\geq 50\%$ stenosis, respectively.

Conclusion: 320-detector CT coronary angiography performed with prospective ECG gating has similar subjective image quality scores, but a 57% lower radiation dose than retrospective ECG gating in a single heartbeat.

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Cardiovascular disease is the leading cause of morbidity and mortality in the West [1]. Early detection of coronary artery disease (CAD) is of vital importance as timely treatment may significantly reduce morbidity and mortality. Although invasive coronary angiography (CAG) remains the standard of reference for the evaluation of CAD, multidetector CT angiography (CTA) has recently emerged as a robust imaging modality for the non-invasive evaluation of CAD [1–7]. Advances in CTA technology have led to continuous improvements in image quality, as well as a reduction in radiation dose and contrast material [8–10]. Recently, 320-detector CT systems were introduced, with enhanced craniocaudal volume coverage when compared with 64-detector systems. With 16 cm anatomical coverage ($0.5\text{ mm}\times 320$ detectors), this new generation of CT scanners allows image acquisition of the entire heart within a single gantry rotation and one heartbeat. As detector arrays have evolved to expand coverage in the z -axis, the application of prospective electrocardiogram (ECG) gating

has become feasible. Prospective ECG gating protocols with 64-detector systems have been shown to provide a substantial decrease in overall radiation dose to patients, although with some limitations with regard to temporal resolution and artefacts [4]. Dynamic volume 320-detector CT, with full cardiac coverage in one gantry rotation, can now provide prospective ECG gating cardiac images without some of the previous limitations. Specifically, dynamic volume CT provides significant improvements with regard to image quality, temporal uniformity and reduction of artefacts, as well as improvements in patient safety, with a reduction in radiation and contrast doses [6, 7, 9, 10].

The image quality, radiation dose and diagnostic accuracy of 320-detector CT with prospective and retrospective ECG gating have not been reported previously. Therefore, the purpose of our study was to compare the image quality, patient radiation dose and diagnostic accuracy of 320-detector CT with prospective and retrospective ECG gating.

Methods and materials

Patients

This study was approved by our institutional human research committee. All patients underwent cardiac CT

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Table 1. Indications for cardiac CT

Indications	Retrospective gating (n=240)	Prospective gating (n=240)
Chest pain	94 (39.17)	96 (40)
Elevated cardiovascular risk	48 (20)	50 (20.83)
Post-operative evaluation	24 (10)	26 (10.83)
Pre-operative evaluation	15 (6.25)	12 (5)
Abnormal echocardiogram	35 (14.58)	37 (15.42)
Positive stress test	24 (10)	19 (7.92)

Data are numbers of patients, and data in parentheses are percentages. χ^2 comparison of groups resulted in value of 0.65.

for a variety of clinical indications (Table 1). Clinical exclusion criteria for cardiac CT included severe allergy to iodine-containing contrast material, history of renal disease (calculated glomerular filtration rate $<60 \text{ ml min}^{-1} 1.73 \text{ m}^{-2}$), pregnancy, non-sinus rhythm, severe respiratory or cardiac failure and inability to achieve a heart rate <65 beats per minute with the use of β -blockers. All patients with a resting heart rate >64 beats per minute received an oral β -blocker (50–100 mg metoprolol tartrate tablets; Astrazeneca, Wuxi, China) administered 45–60 min before scanning. Also, 0.5 mg of sublingual nitroglycerine (nitroglycerine tablets; Yimin Pharma, Beijing, China) was administered 2–4 min before cardiac CT, unless contraindicated. There were no patients with a contraindication to β -blockade, and there were no observed or reported side effects from metoprolol. There were no complications and all patients left the department in a stable condition immediately after image acquisition.

Prospective group

Between November 2009 and August 2010, 240 consecutive clinically indicated cardiac CT examinations were performed with prospective gating at our hospital. Patients with a clinical need for cardiac functional information from the entire R–R interval (the interval between the R-wave of one heartbeat to the R-wave of the next) (such as those who underwent wall motion analysis, those with valve motion abnormalities or those in whom ejection fraction was calculated) or whose heart rate was ≥ 65 beats per minute after administration of β -blockers were not examined with this technique.

Retrospective group

Between November 2009 and August 2010, 240 consecutive patients with heart rates <65 beats per minute and a clinical need for cardiac function information from the entire R–R interval were examined with retrospective gating at our hospital. Patients whose heart rate was ≥ 65 beats per minute after administration of β -blockers were excluded.

Patients were matched on the basis of sex, age (younger than 40 years, 41–50 years, 51–60 years, 61–70 years and older than 70 years) and heart rate (<50 beats per minute, 51–55 beats per minute, 56–60 beats per minute and 61–64 beats per minute). Also, patients were matched on the basis of the clinical indications for cardiac CT (Table 1).

CT technique

CTA studies were performed by using a 320-detector CT scanner (Aquilion ONE; Toshiba Medical Systems, Ottawara, Japan) with 320 detector rows (each 0.5 mm wide) and a gantry rotation time of 350 ms. The phase window was set at 65–85% of the R–R interval in patients with a heart rate <65 beats per minute in prospective scanning. In patients requiring left ventricular function measurements, retrospective ECG-triggered dose modulation was used, scanning an entire cardiac cycle and attaining maximal tube current at 65–85% of the R–R interval. When retrospective dose modulation was used, the tube current outside of the pre-defined interval was 25% of the maximal tube current.

Tube voltage and current were adapted to body mass index (BMI) and thoracic anatomy. Tube voltage was 100 kV (BMI $<25 \text{ kg m}^{-2}$), 120 kV (BMI $25\text{--}35 \text{ kg m}^{-2}$) or 135 kV (BMI $>35 \text{ kg m}^{-2}$) and maximal tube current was 400–580 mA (depending on body weight and thoracic anatomy). A biphasic injection of intravenous contrast was used and the total amount of non-ionic contrast medium (Isovue-370; Bracco Diagnostics, Guangzhou, China) injected into the antecubital vein was 50–70 ml (depending on BMI). 50–70 ml of contrast media was administered at a flow rate of 6.0 ml s^{-1} , followed by a saline flush of 20 ml at a flow rate of 4.0 ml s^{-1} . In order to synchronise the arrival of the contrast medium and the scan, bolus arrival was detected using automated peak enhancement detection in the left ventricle using a threshold of 200 HU. All images were acquired during an inspiratory breath-hold of 10 s. An initial data set was reconstructed at 75% of the R–R interval, with a slice thickness of 0.50 mm and a reconstruction interval of 0.25 mm.

Post-processing

For each patient, the reconstruction phase with minimum artefact was determined at the CT console by reconstructing those 5% intervals available. In those patients for whom a motion-free phase was not identified, image reconstruction proceeded to 1% intervals around the 5% intervals with fewest motion artefacts. Then the images were transferred to an image post-processing workstation (Vitrea 2.0; Vital Images, Minnetonka, MN). Image sets available on the workstation included axial reconstructed images sent from the CT unit, multiplanar reconstruction, curved planar reconstruction rotated through 360° along the course of each coronary artery and major side branches, and thin-slab maximum-intensity projection images created at the workstation.

CT image quality analysis

Two reviewers with more than 4 years of chest CT experience and cardiac CT experience reviewed all CT images. The reviewers were not informed of the patients' clinical information and evaluated images independently at different times. Coronary 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 guidelines [11]. Cardiac CT segment image quality was scored with a four-point Likert scale [7]. Segments that could not be evaluated were assigned a score of 4, corresponding to a lack of vessel wall definition due to marked motion artefact, poor vessel opacification, prominent structural discontinuity or high image noise-related blurring that resulted in absence of diagnostic information. Segments that could be evaluated were scored as follows: a score of 3 corresponded to some motion artefacts or noise-related blurring, fair vessel opacification or minimal structural discontinuity; a score of 2 corresponded to minor motion artefacts or noise-related blurring, good vessel opacification and no structural discontinuity; and a score of 1 corresponded to absence of motion artefacts or noise-related blurring, excellent vessel opacification and no structural discontinuity. For any segment image quality score, if the reviewers differed by only one image quality score after their separate reading sessions, the higher numerical score 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 during a third session in which the reviewers read images together at the same time to reach a consensus.

Radiation dose

The dose-length product displayed by the CT unit was recorded for each cardiac CT examination. The effective dose (measured in millisieverts) was calculated by multiplying the dose-length product by the conversion factor. The conversion factor relating dose-length product to effective dose from coronary CT angiography is uniformly $0.028 \text{ mSv mGy}^{-1} \text{ cm}^{-1}$ for cardiac CT [12].

Coronary angiography procedure

CAG was performed with standard techniques and at least 2 different views were obtained for each main vessel in 41 patients in our study. The CAG, with a spatial and temporal resolution of 0.2 mm and 5 ms, respectively, is associated with an effective dose of about 5.6 mSv. All segments were evaluated by a skilled observer who was unaware of the results of CTA. Quantitative coronary angiography was performed using CMS (Medis, Leiden, the Netherlands) and $\geq 50\%$ reduction of minimal lumen diameter compared with the proximal reference was defined as significant stenosis. All coronary segments were analysed regardless their vessel diameters.

Statistical analysis

The statistical software package used for data analysis was SPSS v. 16.0 for Windows (SPSS Inc., Chicago, IL). Comparison of patient data between the two groups was performed by using a *t*-test for continuous covariates, such as age, and by using a χ^2 test for categorical variables, such as sex. Agreement of image quality scores

was assessed by κ statistics. Agreement was classified as follows [4]: fair ($\kappa=0.21\text{--}0.40$), moderate ($\kappa=0.41\text{--}0.60$), good ($\kappa=0.61\text{--}0.80$) and very good ($\kappa=0.81\text{--}1.00$). Resolved scores in the two groups were compared by using proportional odds ordinal logistic regression analysis with empirically corrected standard errors. Sensitivity, specificity, positive predictive value (PPV) and negative predictive value (NPV) for CTA to detect significant stenosis were calculated from the χ^2 test of contingency.

Results

Matching of groups

Of the 480 patients, 9 were excluded because more than 1 heartbeat was required at the time of scanning. The prospective and retrospective technique allowed acquisition of the data set in 1 heartbeat in 471 cases (Figure 1). Patients in the prospective gating group and those in the retrospective gating group did not differ significantly in terms of their indications for examination. There was no significant difference between the groups for heart rate, sex, age, BMI and patients with one heartbeat at the time of scanning (Table 2).

Image quality

Agreement between the reviewers for segment image quality scores was good ($\kappa=0.73$). 42 segments (23 in

Figure 1. (a) Prospective electrocardiogram (ECG) gating and (b) retrospective ECG gating. With prospective gating, the X-ray beam is on for about 20% of the R-R interval. With retrospective gating, the X-ray beam is on an entire cardiac cycle and maximal tube current is at 65–85% of the R-R interval. The tube current outside of the pre-defined interval is 25% of the maximal tube current. The shaded region represents X-ray exposure time.

Figure 2. (a) Prospectively gated CT image of a right coronary artery with some motion artefact or noise-related blurring and fair vessel opacification (score of 3). (b) Prospectively gated CT image of a right coronary artery with minor motion artefact or noise-related blurring, good vessel opacification and no structural discontinuity (score of 2). (c) Prospectively gated CT image of a right coronary artery with no motion artefact or noise-related blurring, excellent vessel opacification and no structural discontinuity (score of 1).

prospective group and 19 in retrospective group) were not possible to evaluate because of small vessel diameter (<1.5 mm). There were 7023 coronary artery segments ≥ 1.5 mm (3502 in prospective group and 3521 in retrospective group). Of the 7023 coronary artery segments, the image quality scores of prospective group and retrospective group were not significantly different (Figure 2; Table 3).

Radiation dose

When scanning prospectively, with a full dose at 65–85% of the R–R interval, estimated mean radiation dose was 10.0 ± 3.5 mSv (range 6.2–16.6 mSv). The estimated mean radiation dose for retrospectively ECG-triggered modulated scans was 23.2 ± 3.4 mSv (range 17–27.4 mSv). The mean effective radiation dose was 57% lower for prospective gating than for retrospective gating ($p < 0.01$).

CT angiography and coronary angiography analysis

In total, 18 patients in the prospective group and 23 patients in the retrospective group underwent CAG. 615 coronary artery segments (41 patients $\times$ 15 segments per patient) were imaged by CAG, and of these 5 (2 segments in the prospective group and 3 segments in the retrospective group) were not evaluated by CTA because of small vessel diameter (<1.5 mm).

Table 2. Patient characteristics

Characteristic	Retrospective gating (n=240)	Prospective gating (n=240)	p-value
Heart rate (beats per min)	56 ± 6	56 ± 8	0.56
Age (years)	45 ± 16	45 ± 20	0.37
Male ^a	156 (69)	163 (71)	0.42
BMI	21 ± 7	22 ± 9	0.27
1 heartbeat	235	236	0.31
>1 heartbeat	5	4	0.35

BMI, body mass index.

Unless otherwise indicated, data are mean $\pm$ standard deviation.

^aData are numbers of patients, and data in parentheses are percentages.

Of the 55 segments (30 segments in the prospective group and 25 segments in the retrospective group) that had $\geq 50\%$ narrowing on CAG, 52 (28 segments in the prospective group and 24 segments in the retrospective group) were correctly detected by CTA (Figure 3). Three segments of coronary artery with a significant lesion were underestimated and classified as non-significant by CTA (*i.e.* false negative) owing to motion artefacts and poor contrast/noise. Five (two segments in the prospective group and three segments in the retrospective group) non-significant lesions were misdiagnosed and judged as significant by CTA (*i.e.* false positive). Out of these lesions, two were partially or completely calcified and two were in segments in which image quality was judged to be moderate or poor owing to motion artefacts. Only one out of the five false-positive lesions was in a segment judged to be of moderate quality owing to poor contrast/noise. Compared with CAG, the results for prospective ECG gating *vs* retrospective ECG gating were 92% *vs* 90% for sensitivity ($p = 0.23$), 89% *vs* 91% for specificity ($p = 0.19$), 90% *vs* 93% for PPV ($p = 0.25$) and 92% *vs* 95% for NPV ($p = 0.21$) for lesions with $>50\%$ stenosis, respectively. The inter- and intra-observer κ -values for the CTA evaluation of stenosis were 0.95 and 0.93, respectively.

Discussion

Since the establishment of 64-detector cardiac CT, the hardware advances have focused on temporal resolution and craniocaudal volume coverage. Dual-source CT was designed to improve temporal resolution to 83 ms, improving image quality by reducing motion artefact [3].

Table 3. Image quality scores

Image quality scores	Retrospective gating (%)	Prospective gating (%)	p-value
1	76 (2662/3502)	77 (2711/3521)	0.41
2	20 (700/3502)	18 (634/3521)	0.23
3	4 (140/3502)	5 (176/3521)	0.18
4	0 (0/3502)	0 (0/3521)	

Data in parentheses are raw data used to calculate the percentages.

Figure 3. (a) Three-dimensional volume-rendered image, (b) curved multiplanar reconstruction image and (c) coronary angiography image show significant lesions (arrows) in the mid-left anterior descending artery in a 52-year-old male patient.

The development of 320-detector CT with wide area detector has enabled whole heart coverage, in theory reducing patient radiation by eliminating helical overlapping [6, 7, 13]. There are theoretical advantages of this system with respect to image quality. First, 320-detector cardiac CT eliminates “stair-step” artefacts inherent in 64-detector CT that image subvolumes of the entire cardiac volume over multiple gantry rotations. Second, the subsecond acquisition of the entire cardiac volume allows the contrast bolus to be imaged at a single time point.

Traditional helical cardiac CT imaging requires table movement that transports the patient through the projection of the X-ray beam. CT angiography requires a relatively low beam pitch and thus slows table movement. Overlapping exposures to the patient come at the cost of a higher radiation dose [14–15]. Wide area detector CT, with full cardiac coverage, does not require an overlapping radiation exposure and will provide significant radiation dose savings for cardiac imaging compared with 64-detector systems [6, 7, 13]. Prospective ECG gating, where only a portion of one R–R interval will need to be exposed, has the capability of further reducing radiation doses for coronary angiography [16–19]. The advantages of retrospective CT angiography over prospective CT angiography include the ability to acquire systolic-phase information and the chance to assess ventricle motion and aortic valve motion. Patients with a low probability of myocardial infarction and no history of coronary heart disease who were examined to rule out CAD might reap the most benefits from the large radiation dose reduction with prospective ECG gating, as the advantages of retrospective CT angiography are typically not needed in this group.

In this study, we compared a group of patients who underwent prospectively gated cardiac CT with a group of patients who underwent retrospectively gated cardiac CT and who were closely matched for heart rate, age,

sex, BMI and clinical indications. We found similar image quality scores for the coronary artery segments between the prospective gating group and the retrospective gating group. Though only a small percentage of patients had direct correlation with CAG, which limits the accuracy of data in the present study, our results initially indicate that the diagnostic accuracy of CTA with prospective gating *vs* retrospective gating was not significantly different. So, 320-detector CTA performed with prospective ECG gating is acceptable for daily clinical practice. We also found that radiation dose in prospective gating group was 57% lower than that in retrospective gating group. Steigner et al [8] found that a phase window width of 10% will reduce patient radiation and yield diagnostic images in >90% of patients for prospectively ECG-gated single heartbeat coronary CTA. de Graaf et al [10] reported that sensitivity, specificity, and PPVs and NPVs to detect $\geq 50\%$ luminal narrowing on a patient basis were 100%, 88%, 92%, and 100%, respectively. Our results would tend to agree with the findings of these authors. To the best of our knowledge, this is the first study to compare image quality, diagnostic accuracy and radiation dose in 320-detector cardiac CT between prospective ECG gating and retrospective ECG gating in a single heartbeat in a large clinical setting.

Rybicki et al [7] recently reported that the mean dose was 6.8 ± 1.4 mSv for the most common protocol with a conversion factor of 0.017 (120 kV, 400 mA, prospective ECG gating, 60–100% phase window, 16 cm cranio-caudal coverage, single heartbeat). The effective mean radiation dose calculated with the conversion factors of 0.028 was 10.0 ± 3.5 mSv (range 6.2–21.6 mSv) in the present study, which was higher than that reported by Rybicki et al [7]. The conversion factor for cardiac CT in this study is at least double that previously reported, so the effective radiation dose in our study is almost twice as much as that previously published. Gosling et al [12]

reported there was increasing evidence that previously published chest conversion factors (when applied to cardiac CT) significantly underestimate the effective dose to the patient. This is due to two factors: (1) the change in the International Commission on Radiological Protection tissue weighting factors mentioned earlier; and (2) the marked difference in scan volume between cardiac and whole-chest CT scans. Cardiac CT scans only irradiate the lower chest and upper abdomen, a scan field that involves irradiating the breast tissue for the majority of the scan volume rather than including the relatively radio-insensitive tissues of the upper chest. So, a conversion factor of 0.028 would give a better estimation of the effective dose from prospectively gated cardiac CT [12].

Recently, several new approaches have been developed to reduce cardiac CT radiation dose. First, dose modulation was introduced, allowing tube current modulation throughout the cardiac cycle, decreasing radiation exposure at the cost of increased image noise during low tube current [7–9]. Subsequently, prospective ECG triggering became available, allowing data acquisition during a narrow, pre-defined portion of the R–R interval (usually end-diastolic phase when the heart is relatively motion free), resulting in a substantial reduction in radiation dose [8, 16, 17]. Importantly, volumetric data acquisition used by 320-detector CT may further reduce radiation exposure by eliminating helical overlapping [6–8]. Indeed, in the current study, using 320-detector CT in combination with prospective ECG triggering, radiation doses as low as 6.2 mSv were achieved in patients with a low and stable heart rate, whereas diagnostic image quality was maintained in 95% of the patients scanned. Other technical advances, such as adaptive collimation and high-pitch spiral acquisition, may also allow significant radiation reduction using scanning techniques requiring multiple heartbeats [16, 19].

Our study had several important limitations. First, our study population consisted of patients with a high prevalence of CAD, which might have resulted in an overestimation of the diagnostic accuracy. Second, though our good κ score for reviewers' agreement in coronary artery segment image quality suggests reproducibility, scoring of image quality on a Likert scale is a subjective process. Third, the image quality scoring scales that have been used by other investigators of cardiac CT image quality were arbitrary in our study. Fourth, only a small percentage of patients had direct correlation with CAG, which limits the accuracy of the data. Finally, our results need to be confirmed in a blinded prospective randomised study that includes other patient populations from multiple institutions.

In conclusion, our findings suggest that 320-detector cardiac CT performed with prospective ECG gating has similar subjective image quality and substantially lower patient radiation dose than retrospective ECG gating in a single heartbeat. If proved by further investigations, a single heartbeat prospective ECG gating scan may have clinical utility in patients for whom lower radiation dose is important. However, benefits from prospectively gating cardiac CT must be weighed against two current limitations. One is that imaging at heart rates >64 beats per minute is not recommended, and the other is that functional cardiac information is not obtained.

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