Dose and image quality comparison between prospectively gated axial and retrospectively gated helical coronary CT angiography

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Objective: Our aim was to compare image quality, coronary segment assessability and radiation dose in prospectively gated axial (PGA) coronary CT angiography (CTA) and conventional retrospectively gated helical (RGH) coronary CTA.

Methods: Institutional review committee approval and informed consent were obtained. RGH CTA was performed in 41 consecutive patients (33 males, 8 females; mean age 52.6 years), then the PGA CTA technique was evaluated in 41 additional patients (24 males, 17 females; mean age 57.3 years) all with a pre-scan heart rate of ≤ 70 beats per minute (bpm). Two radiologists, blinded to clinical information, independently scored subjective image quality on a five-point ordinal scale.

Results: The mean effective dose in the PGA group was 4.7 ± 0.9 mSv, representing a 69% dose reduction compared with the RGH CTA group (15.1 ± 1.9 mSv, $p < 0.001$). The mean segmental image quality score was significantly higher in the PGA group (3.4 vs 3.2) than in the RGH CTA group ($p < 0.005$). The percentage of assessable segments was 98.1% in the PGA group and 97.3% in the RGH group ($p = 0.610$).

Conclusion: PGA CTA offers a significant reduction in radiation dose compared with RGH CTA, with comparable image quality for patients with heart rates below 70 bpm.

Received 6 September 2009

Revised 10 February 2010

Accepted 1 March 2010

DOI: 10.1259/bjr/13222537

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Rapid advances in multidetector CT (MDCT) technology have enabled non-invasive coronary angiography with high diagnostic accuracy [1–4]. However, the potential radiation risks associated with standard retrospectively gated helical (RGH) techniques for MDCT-based coronary CT angiography (CTA) have become a concern [5, 6]. Reported radiation doses from coronary CTA have ranged from 11 to 27 mSv [1, 7–10]: nearly 2–4 times the radiation dose attributed to typical invasive diagnostic angiography [11, 12]. Consequently, reducing cardiac CT doses to levels as low as reasonably achievable has become a major issue. A new prospectively gated axial (PGA) acquisition protocol has recently been introduced [13] to reduce the radiation dose by scanning only the mid-diastolic phase [8–10] of the cardiac cycle. The acquisition is based on a prospective electrocardiogram (ECG)-triggered sequential axial acquisition mode in opposition to the standard retrospectively gated continuous helical acquisition. Our aim was to compare image quality and radiation dose of PGA-based coronary CTA with the standard helical mode on a 64-channel CT.

Methods and materials

Patients

After local hospital ethics committee approval and informed consent were obtained for each patient, the coronary CTAs from 82 patients scanned from November 2007 to March 2008 were retrospectively included in this study. A standard RGH CTA protocol was evaluated in 41 consecutive patients (33 males, 8 females; mean age 52.6 years) and a PGA CTA protocol in 41 additional patients (24 males, 17 females; mean age 57.3 years). Exclusion criteria for cardiac CT included severe allergy to iodine-containing contrast material, a history of renal failure, pregnancy, arrhythmia, severe cardiac failure, inability to achieve a heart rate below 70 beats per minute (bpm) with the use of β -blockers, or the presence of a pacemaker, a coronary bypass graft or stent. When needed, 2.5–5 g of an iv β -blocker (Brevibloc, Baxter, Maurepas, France) was injected immediately before the CTA acquisition. A heart rate below 70 bpm is needed to ensure good image quality in the PGA CTA since its temporal resolution is 210 ms. Sublingual isosorbide dinitrate (Isocard, Substipharma, Paris, France) was administered 5 min prior to examination. A dual-head injector (Injektron CT2, Saarbrücken, Germany) was

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used for all the examinations with automatic bolus tracking triggered when enhancement in a region of interest placed in the ascending aorta reached a threshold of 200 HU. The acquisition was performed after the injection of 1.0 ml kg^{-1} body weight of Iomeron 400 (Bracco, Courcouronnes, Paris, France) at 5.5 ml s^{-1} , followed by an injection of 50 ml of saline chaser at the same flow rate. All examinations were performed on a 64-channel scanner (Brilliance CT, Philips Healthcare, Cleveland, OH).

RGH CTA protocol

The RGH protocol included a collimation of $64 \times 0.625 \text{ mm}$ (40 mm) with a gantry rotation time of 0.42 s and a pitch factor of 0.2. Pitch was not adjusted according to heart rate, as all patients scanned with the RGH protocol had a heart rate of $\leq 70 \text{ bpm}$. All patients were scanned with continuous table movement in the craniocaudal direction, using a tube voltage of 120 kVp and an effective mAs set according to patient size: 600 mAs (tube current: 286 mA) for patients who weighed $\leq 90 \text{ kg}$ (36 patients), 800 mAs (tube current: 381 mA) for patients who weighed 90–110 kg (4 patients), and 1000 mAs (tube current: 476 mA) for patients who weighed $>110 \text{ kg}$ (1 patient). To ensure image quality comparisons with an optimal reference, the maximum number of available phases was desired. Therefore, no ECG-gated dose modulation was used for the RGH protocol in our study.

PGA CTA protocol

PGA sequential acquisitions (Step & Shoot Cardiac, Philips Healthcare) were performed in the craniocaudal direction with ECG synchronisation using a $64 \times 0.625 \text{ mm}$ (40 mm) detector collimation, a tube voltage of 120 kVp, a tube current-time product of 210 mAs (tube current: 500 mA) and a rotation time of 0.42 s. To ensure optimal signal-to-noise ratio in the initial experience PGA images, the X-ray technique was not adjusted according to patient weight.

In the PGA protocol, the cardiac anatomy of interest is covered by a series of sequential axial scans prospectively triggered at a quiescent physiological phase [14], typically in mid-diastole (75%) for patients with heart rates of $<65\text{--}70 \text{ bpm}$. For each axial scan, a 40 mm volume of data is acquired with the table stationary while the X-ray tube and detector rotate around the patient. After an axial acquisition is completed at one location, the table is indexed to the next location for the subsequent scan, which is again prospectively triggered via ECG. To enable full three-dimensional cone-beam reconstruction, the table is indexed 32 mm (8 mm overlap) between acquisitions, typically resulting in 3–5 acquisitions to cover the entire cardiac anatomy, skipping one heart cycle between each axial acquisition. During each axial acquisition, X-ray exposure occurs for only a single cardiac phase. Similar to the 50–100 ms buffer reported by Earls et al [8], our vendor's CT system provided an additional $\pm 70 \text{ ms}$ buffer for each axial location to account for heart rate variation during the scan.

Post-processing and image quality evaluation

Coronary artery segments were defined according to a modified 15-segment American Heart Association classification [15] to which we added the ramus intermedius as segment 16. All CT images were read by two cardiac imaging-trained radiologists (CH and HC; 3 and 4 years of experience, respectively). Reviewers retrospectively evaluated the images separately, and were not aware of the clinical indication. A workstation (Brilliance Workspace v3.5, Philips Healthcare) was used to review images from all examinations. For the PGA CTA group, the reviewers analysed a single cardiac phase (75%). For the RGH CTA group, the reader reviewed the 75% phase but was given the option to select an additional phase(s) from reconstructions between 0% and 90% of the cardiac cycle in 10% increments as needed. Native axial, curved multiplanar reformatted, thin-slab maximum-intensity projection images were used for image quality assessment.

Coronary segments were scored using a five-point ordinal grading scale. Segments not visible, without contrast opacification, or with large discontinuities impairing the vessel assessability were classified as non-assessable (score, 1). Assessable segments were classified as fair (score, 2) when they had blurred borders or fair contrast opacification or minor vessel discontinuity; average (score, 3) when they had moderately blurred borders and adequate contrast opacification; good (score, 4) when they had slightly blurred borders and good contrast opacification or minor vessel discontinuity; and excellent (score, 5) when they had sharply defined borders and excellent contrast opacification with no vessel discontinuity. All segments were included for assessment, regardless of vessel calibre. A stair-step artefact was reported when present.

Radiation dose

The dose-length product, as displayed on the dose report of the CT scanner, was recorded. No dose measurements were performed. The effective dose in millisieverts was calculated by multiplying the dose-length product by the chest conversion coefficient k ($0.017 \text{ mSv mGy}^{-1} \text{ cm}^{-1}$) [16] in order to comply with recent dose evaluation studies [8–10, 17–19]. The mean z-axis coverage was normalised to facilitate a comparison of effective doses in both RGH and PGA series. The mean effective radiation dose in each group was divided by its corresponding mean z-axis coverage then multiplied by 12 cm, an arbitrarily chosen average heart length [9].

Statistical analysis

The statistical analysis of the data was performed using commercially available software (MedCalc v.9.2.1.0, MedCalc Software, Mariakerke, Belgium) and Excel 2003 (Microsoft, Redmond, WA). Discrete results are expressed as counts or proportions in percentages. Continuous variables are presented as mean $\pm$ standard deviation (SD). Interobserver agreement was calculated using κ

statistics and classified as fair ($\kappa=0.21\text{--}0.40$), moderate ($\kappa=0.41\text{--}0.60$), good ($\kappa=0.61\text{--}0.80$) or very good ($\kappa=0.81\text{--}1.00$). Statistical comparisons between the two cohorts were performed using the Student's *t*-test for continuous variables and the Mann-Whitney *U*-test for ordinal rank scores. All tests were two-sided, and a *p*-value <0.05 was considered statistically significant.

Results

Patients

Table 1 demonstrates demographic information and the clinical indication for coronary CTA in both patient groups. There was no significant difference in body mass index (BMI), heart rate, age and clinical indications between the two cohorts.

Radiation dose

The mean ($\pm$ SD) effective dose for the PGA CTA group was 4.7 ± 0.9 mSv (range 3.7–7.7 mSv) and 15.1 ± 1.9 mSv (range 12.3–21.5 mSv) for the RGH CTA group, corresponding to a mean dose reduction of 69% with the PGA CTA method ($p < 0.0001$) (Table 2). The mean 12 cm z-axis coverage normalised effective dose was 3.8 mSv in the PGA CTA group and 11.4 mSv in the RGH CTA group. The mean tube current was 295 ± 29 mA in the RGH CTA technique compared with 500 mA ($p < 0.0001$) in the PGA CTA technique. The tube voltage was the same in both protocols. The mean scan time was significantly greater in the RGH CTA group (11.24 s) than in the PGA CTA group (8.67 s, $p < 0.0001$).

Image quality

Image quality scores were significantly higher in the PGA CTA group with a mean ($\pm$ SD) score of 3.4 ± 0.9 and a median score of 4 (25th–75th percentiles 3–4) than in the RGH CTA group (median score 3; 25th–75th percentiles 3–4; mean score 3.2 ± 0.9 ; $p = 0.003$).

(Figures 1–3). The use of additional reconstructed phases in end-diastole (0%) or end-systole (40%) only served to improve the image quality score in 7 of 556 (1.3%) segments (3 patients) in the RGH CTA group. A total of 536 segments were evaluated in the PGA CTA group, of which 526 (98.1%) were considered assessable with an image quality score ≥ 2 . In the RGH CTA group, 556 segments were evaluated, of which 541 (97.3%) were considered assessable. No significant difference in the percentage of assessable segments between the two groups ($p = 0.61$) was observed. There was good agreement between the image quality scores of the two independent readers ($\kappa = 0.7$).

Coronary artery disease was found in 8 patients in the PGA CTA group and in 14 patients in the RGH CTA group. It could be excluded in 33 patients in the PGA CTA group and in 27 patients in the RGH CTA group. Five patients had unassessable segments in the PGA CTA group, only one of whom had an invasive coronary angiography. Five patients had unassessable segments in the RGH CTA group, only one of whom had an invasive coronary angiography.

A stair-step artefact was found in 9 of the 41 patients, but it impaired the interpretation of the coronary scan in only one patient. In this case, the stair artefact led to a large displacement (more than 50%) of the coronary segment.

Discussion

In this study, we compared a new method of coronary CTA based on a prospectively gated sequential axial acquisition (PGA CTA) with the reference method (RGH CTA) in 82 patients. We demonstrated an important and significant decrease in radiation dose by PGA CTA with an equivalent image quality and number of assessable segments compared with RGH CTA.

Dose

MDCT is usually performed in a helical mode with overlapping pitch that enables adaptive multicycle reconstruction [20] for high temporal resolution. However, this

Table 1. Patient characteristics and clinical indication for coronary CT angiography

	RGH CTA (n=41)	PGA CTA (n=41)
Patient characteristics		
Male	33 (80)	24 (59)
Age ^a (years)	52 ± 14.4	57 ± 15.7
BMI ^a (kg m ⁻²)	25.8 ± 3.7	26.3 ± 3.8
Heart rate ^a (bpm.)	59.8 ± 7.4	56.5 ± 5.4
Clinical indication ^b		
Chest pain	17 (41.5)	16 (39)
Elevated CAD risk factor	8 (19.5)	8 (19.5)
Positive stress test	5 (12.2)	6 (14.6)
Follow up for CAD	2 (4.9)	4 (9.8)
Pre-operative evaluation	3 (7.3)	1 (2.4)
Other	6 (14.6)	6 (14.6)

RGH CTA, retrospectively gated helical CT angiography; PGA CTA, prospectively gated axial CT angiography; BMI, body mass index; bpm, beats per minute; CAD, coronary artery disease.

Unless otherwise indicated, all data are numbers of patients, and data in parentheses are percentages.

^aData are mean $\pm$ standard deviation.

^b χ^2 test for clinical indications resulted in a *p*-value of 0.893.

Table 2. Radiation doses and scanning parameters

	RGH CTA (n=41)	PGA CTA (n=41)	p-value
Mean effective dose (mSv)	15.1 ± 1.88 (12.3–21.5)	4.7 ± 0.87 (3.7–7.7)	<0.0001
Dose-length product (mGy cm)	889 ± 110.56	276 ± 51.16	<0.0001
Scan length (cm)	15.9 ± 2.09	14.7 ± 2.12	0.0089
Scan time (s)	11.2 ± 1.03	8.7 ± 2.11	<0.0001
Tube current (mA)	295 ± 29	500 ± 0	<0.0001
Tube voltage (kV)	120	120	NA
Collimation	64 × 0.625 mm	64 × 0.625 mm	NA

All data are mean ± standard deviation (range, minimum – maximum).

RGH CTA, retrospectively gated helical CT angiography; PGA CTA, prospectively gated axial CT angiography; NA, not applicable.

overlapping pitch results in redundant exposure of chest tissue. Reported effective doses by RGH CTA have ranged from 11 to 27 mSv [1, 7–9], which is two to four times the radiation dose of a typical diagnostic invasive angiography [11, 12]. The optimisation of the radiation dose has become a major issue since MDCT scanners were introduced [5, 6]. Several strategies have been used in recent studies to try to overcome this increase in radiation dose. The use of reduced tube voltage has been demonstrated to significantly reduce effective dose, but is only appropriate in patients with a small body habitus and may adversely affect image quality in overweight patients [7, 21, 22]. Although the continuous table movement of RGH scans requires X-ray exposure during the entire R–R period, the most useful interval of the cycle for coronary artery evaluation is the quiescent, mid-diastolic phase in patients with a low heart rate [14]. Dose reduction strategies for RGH CTA such as ECG-dependent tube current modulation have exploited this fact by applying a nominal tube current in the mid-diastolic phase and a reduced current (typically 20% of nominal) for other phases of the cycle. The current modulation strategy has enabled a significant reduction in radiation dose by RGH coronary CTA down to 8–19 mSv without impairing the diagnostic capability of MDCT [1, 5, 7, 21, 23, 24].

The PGA protocol we evaluated in this study consists of delivering radiation to the patient only during the mid-diastolic phase [8–10, 13] in a sequential axial mode.

This prospectively gated technique results in a significant decrease in radiation dose (4.7 ± 0.8 mSv), achieving values close to those observed in typical invasive diagnostic angiography (2–5 mSv) [11, 12] and significantly lower than helical MDCT angiography values (15.1 ± 1.9 mSv). The mean PGA CTA radiation dose observed in our study is consistent with other recent studies comparing prospectively and retrospective gated acquisitions. Table 3 summarises dose data from recently published evaluations of PGA CTA and the data observed in our study. Our reported 4.7 mSv mean effective PGA dose, corresponding to a z-axis length of 14.7 cm, is reduced to 3.8 mSv when normalised to a 12 cm z-axis length. Earls et al [8] observed a mean effective dose of 2.8 mSv for a 12.8 cm scan length and a 12 cm normalised dose of 2.6 mSv. Shuman et al [9] reported a mean effective PGA dose of 4.2 mSv with a normalised z-axis length of 12 cm. Husmann et al [19] and Scheffel et al [18] reported mean effective doses of 2.1 and 2.5 mSv for scan lengths of 13.0 and 14.1 cm, respectively, by PGA. Corresponding 12-cm normalised doses result in effective doses of 1.9 and 2.1 mSv for Husmann and Scheffel, respectively. Hirai et al [10] obtained a mean effective dose of 4.1 mSv for the PGA protocol, but no information about the z-axis length was provided. Most recently, Maruyama et al [17] reported mean effective doses of 4.3 mSv for PGA acquisition and 21.1 mSv for RGH.

Figure 1. Coronary segment image quality scores with a similar distribution between the RGH CTA (retrospectively gated helical CT angiography) and PGA CTA (prospectively gated axial CT angiography) groups. Very few segments were non-assessable (score 1: PGA CTA, 1.9%; RGH CTA, 2.9%). The majority of the coronary segments were assessable and rated fair (score 2: PGA CTA, 15.5%; RGH CTA, 16.4%), good (score 3: PGA CTA, 29.2%; RGH CTA, 37.4%), very good (score 4: PGA CTA, 47.7%; RGH CTA, 40.3%) or excellent image quality (score 5: PGA CTA, 5.8%; RGH CTA, 3.1%) in both techniques. The PGA CTA cohort had fewer segments that scored 3 and more segments that scored 4 and 5 than the RGH CTA cohort.

Figure 2. RGH CTA (retrospectively gated helical CT angiography) curved multiplanar reformatted image of the right coronary artery with slightly blurred borders, good opacification and no vessel discontinuity (score 4).

The relative dose reduction (69%) was lower in our study than in the studies cited above [8–10], which showed 77–83% dose reductions by PGA compared with RGH. While some of the difference is attributed to the lack of patient weight-adapted PGA protocols in our study, the primary factor is the significantly lower effective dose in our RGH CTA cohort. It is interesting to note that, although we chose not to use ECG-based dose modulation in our RGH CTA reference group, Earls et al and Shuman et al did use ECG-based dose modulation for their RGH patients, but still reported higher absolute 12 cm normalised effective doses (16.1 and 18.1 mSv, respectively) than the 11.4 mSv RGH dose in our study. While the higher 12 cm normalised dose

Figure 3. PGA CTA (prospectively gated axial CT angiography) curved multiplanar reformatted image of the right coronary artery with no motion artefacts, good opacification and no vessel discontinuity (score 5).

reported by Earls et al may be attributed in part to a higher mean BMI in the RGH group than that reported in our study, no patient size was reported by Shuman et al.

While informative for comparative purposes in heterogeneous patient groups, a normalisation of dose to a 12 cm scan length [9] is not practical as a reference in clinical practice for two primary reasons: (1) it underestimates the typical observed coronary CTA scan lengths of 14.4 ± 3.7 cm [7] reported in the literature; and (2) it neglects to account for the discrete nature of PGA acquisitions, which acquire sequential axial acquisitions in fixed numbers of steps. An exact 12 cm scan length cannot currently be achieved in a discrete PGA mode, and the difference in dose from one additional shot beyond the typical 3 or 4 (12.8–14 cm) acquisitions can be 20–25%. In this way, a 12 cm normalised dose will probably always underestimate CTA dose, especially by PGA, in clinical practice.

Image quality

The comparison of image quality scores between the PGA CTA and the RGH CTA techniques yielded similar results for the number of assessable segments in both groups, with a significant superiority of mean quality score in the PGA CTA mode. We hypothesise that this improved image quality may be attributed in part to the absence of table motion during the PGA acquisition. Thus, even with the potential for an additional type of artefact (stair-step) to be observed in sequential PGA CTA images, the number of non-assessable segments is not significantly different from that in the RGH CTA mode. Moreover, in a recent study, Hirai et al [10] found equivalent diagnostic performance in the assessment of coronary stenosis for PGA and RGH CTA. In rare conditions, a stair-step artefact can seriously impair the diagnostic capacity of PGA-based coronary CT when it occurs in the left main coronary artery, which is typically superior to the proximal right coronary artery. The first acquisition on a 40 mm detector scanner is usually wide enough to prevent a stair-step artefact on the left main artery, but the position of the heart relative to the expected z-location in a scout image may be modified by deep inspiration before the PGA CTA acquisition. If this occurs concomitantly with significant heart rate variation (e.g. Valsalva response), stair-step artefacts may result and impair diagnosis (Figure 4). However, even if a repeat examination is warranted, the combined effective radiation dose of two PGA CTs is likely to be less than even an ECG-based dose-modulated RGH scan. Furthermore, in new generation 320-detector scanners, the detector coverage is significantly wide enough to ensure entire heart coverage with a single axial acquisition. The transition between the first and second axial acquisition does not pose a risk of stair-step artefact in the main left coronary artery.

Although we report that PGA CTA provides an important dose reduction without adversely affecting image quality, it should only be performed in patients with a heart rate below 70 bpm. Unlike the adaptive multicycle reconstruction afforded by RGH CTA [20], PGA techniques are limited to temporal resolution of

Table 3. Comparison of reported BMIs, weight, z-axis length, effective dose and 12 cm z-axis normalised doses for prospectively gated axial evaluation studies in the literature

Study	BMI (kg m^{-2}) (weight, kg)		z-axis length (cm)		Effective dose (mSv)	
	PGA	RGH	PGA	RGH	PGA	RGH
Earls et al [8]	28.3	27.6	12.8	13.8	2.8	18.4
Shuman et al [9]	–	–	18.3	17.9	6.2	26.7
Hirai et al [10]	(62)	(62)	–	–	4.1 ^b	20
Scheffel et al [18]	26.2	NA	14.1 ^a	NA	2.5	NA
Husmann et al [19]	26.1	NA	13.0	NA	2.1	NA
Maruyama et al [17]	23.9	24	13.4 ^a	15.6 ^a	4.1	21.1
Hlaiheli et al (this study)	26.3 (76)	25.8 (77)	14.7	15.9	4.7 ^b	15.1

All data are means. BMI, body mass index; RGH, retrospectively gated helical; PGA, prospectively gated axial; NA, not applicable.

^aScan length calculated from the ratio of reported dose length product to CT dose index and averaged from two patient groups (100 and 120 kVp).

^bAll studies used a patient weight-based adapted radiographic technique for the PGA protocol, except this one. Our study used a maximum mA protocol for all PGA patients to ensure an optimal signal-to-noise ratio for comparative image quality assessment.

single-cycle reconstruction algorithms. Consequently, β -blockers are needed to reduce heart rate and prevent rhythm change during the examination. Their use can increase the number of patients who can benefit from a PGA CTA protocol. Many patients clinically indicated for coronary CT angiography already receive β -blockers as part of a pharmacological therapy regimen. If not, they may be given orally, a few hours before the examination, or by iv injection prior to the CTA acquisition. Furthermore, since PGA CTA prospectively targets a single cardiac phase of interest, comprehensive ventricular function analysis, including left ventricular volumes, stroke volumes and ejection fractions, cannot be assessed with images obtained with a PGA acquisition. The absence of additional cardiac phases may also limit the analysis of the coronary arteries in challenging cases (*e.g.* high heart rate variation) where, for example, reconstructed images from end-systolic phases often augment diagnosis. Nevertheless, in our study, the end-systolic phases were useful in only 3 of 41 patients and in 7 of 556 segments.

While subtle differences exist in dose and image quality results reported in our study compared with the published literature, our results tend to agree with the findings of these authors, confirming that prospectively gated CT angiography techniques are feasible on CT scanners from multiple vendors and confer similar benefits.

A limitation to our study is the lack of correlation of the CT image data with invasive coronary angiography when available. In a recent study, Scheffel et al [18] compared prospectively gated coronary CT angiography in a cohort of 120 patients with a heart rate below 70 bpm with invasive coronary angiography. They reported sensitivity, specificity, positive predictive values and negative predictive values of 100%, 93%, 94% and 100%, respectively. Another limitation of our preliminary study was the fixed X-ray technique applied to all PGA CTA patients. As is usually done in RGH CTA, the adaptation of tube current (or mAs) based on patient weight would have certainly resulted in an additional decrease in the effective radiation dose delivered by CTA and warrants dedicated future study.

(a)

(b)

Figure 4. PGA CTA (prospectively gated axial CT angiography) coronal (a) and curved multiplanar reformatted (b) images demonstrating a stair-step artefact on the main left coronary artery. Invasive coronary angiography showed a normal coronary tree.

Conclusion

Prospectively gated axial coronary CT angiography appears to be a robust diagnostic examination for coronary artery disease with a significantly reduced radiation dose. When performed in patients with stable heart rates less than 70 bpm, PGA yields image quality equivalent to retrospectively gated coronary CT angiography.

Acknowledgments

We are indebted to the medical and technical staff members of the Computed Tomography Unit for their invaluable contribution and in particular to M Aissat and R Hasquenoh.

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