Singapore Med J 2013; 54(1) : 15

Coronary computed tomography angiography with prospective electrocardiography triggering: a systematic review of image quality and radiation dose

Akmal Sabarudin[1,2], MSc, *Zhonghua Sun*[1], PhD, *Kwan-Hoong Ng*[3,4], PhD

ABSTRACT The purpose of this study was to perform a systematic review of the diagnostic accuracy, image quality and radiation dose of prospective electrocardiography (ECG)-triggered coronary computed tomography angiography (CCTA). We searched databases containing studies of CCTA that used prospective ECG-triggering between 2008 and 2011. The effective dose and image quality reported in each study were analysed and compared between the types of multislice CT scanners. We identified 23 studies through this search, with mean assessable coronary segments and effective dose at 96.8% (95% confidence level [CI] 83%, 100%) and 3.6 mSv (95% CI 2.9, 4.3 mSv), respectively. Both quantitative and qualitative assessments of image quality indicated that image quality was achieved in studies using prospective ECG-triggered CCTA, regardless of the type of CT scanners. The pooled estimates of diagnostic values were more than 90% for patient-, vessel- and segment-based assessments. Prospective ECG-triggered CCTA results in high diagnostic accuracy and image quality, with a significantly low radiation dose.

Keywords: coronary artery disease, coronary CT angiography, image quality, prospective ECG-triggering, radiation dose
Singapore Med J 2013; 54(1): 15–23

INTRODUCTION

Coronary computed tomography angiography (CCTA) has been widely used as a valuable diagnostic imaging modality for the noninvasive assessment of coronary artery disease (CAD). It has become a reliable and accurate modality to assess the coronary arteries of patients with suspected CAD.(1) Previous studies have found that retrospective electrocardiography (ECG)-gated CCTA provides high sensitivity (range 86%–99%) and specificity (range 89%–100%) for coronary artery stenosis, and also results in high negative predictive values (NPVs; range 96%–99%).(2,3) Prospective ECG-gated CCTA also promises high sensitivity (range 93.7%–100.0%), specificity (range 82.7%–97.0%) and NPV (range 95%–98%) in the assessment of CAD.(2,3) Although high diagnostic accuracy is achieved with both retrospective and prospective ECG-gated CCTA for detecting CAD (Fig. 1), the radiation doses associated with these two cardiac examinations are significantly different due to the different approaches used for coronary artery scanning.

It is well known that CCTA with retrospective ECG gating leads to high radiation doses of up to 31.4 mSv since volumetric data of the heart is acquired during continuous scans in this modality, although only a portion of the data is used for reconstruction.(4,5) In contrast, with exposure taking place at selective phases of the cardiac cycle in patients with low and regular heart rate, prospective ECG triggering is associated with very low radiation doses, which indicates a significant reduction in effective doses of up to 87%.(6) Several studies that used prospective ECG-gated CCTA have reported significantly reduced radiation doses.(7-12) However, the diagnostic image quality of prospective triggering in the assessment of coronary arteries or CAD has not been systematically studied. Therefore, the purpose of this study was to investigate previous studies that assessed the coronary artery using prospective ECG-triggered CCTA for the detection of CAD, in terms of image quality and radiation dose via a systematic review of the current literature.

METHODS

Literature search

A search was conducted of the English literature in the MEDLINE, SpringerLink, Highwire Press and Science Direct databases to identify studies performed with prospective ECG-triggered CCTA on patients with suspected or confirmed CAD. The time period of the literature search ranged from 2008, where prospective ECG triggering of CCTA was first reported, to December 2011. The key words used for searching relevant articles included ‘CT coronary angiography’, ‘prospective ECG gating’, ‘multislice CT/multidetector CT with prospective ECG-gating/ECG-triggering’, and ‘image quality/diagnostic value of CT coronary angiography’. Eligible articles were identified and selected based on the following criteria: (a) CCTA was performed while using prospective ECG gating in the study; (b) information on qualitative and quantitative image quality assessments was provided in each study; and (c) the radiation dose associated with CCTA, inclusive of effective dose value, was provided in each study. Case reports, phantom studies, review articles, as well as studies involving paediatric patients or patients who had previously received treatment (coronary stents or bypass grafts), were excluded from the analysis.

---

[1]Department of Imaging and Applied Physics, Curtin University, Perth, Australia, [2]Faculty of Health Sciences, Universiti Kebangsaan Malaysia, [3]Department of Biomedical Imaging, [4]University of Malaya Research Imaging Centre, University of Malaya, Kuala Lumpur, Malaysia

Correspondence: A/Prof Zhonghua Sun, Discipline of Medical Imaging, Department of Imaging and Applied Physics, Curtin University, GPO Box U1987, Perth, WA 6845, Australia. z.sun@curtin.edu.au

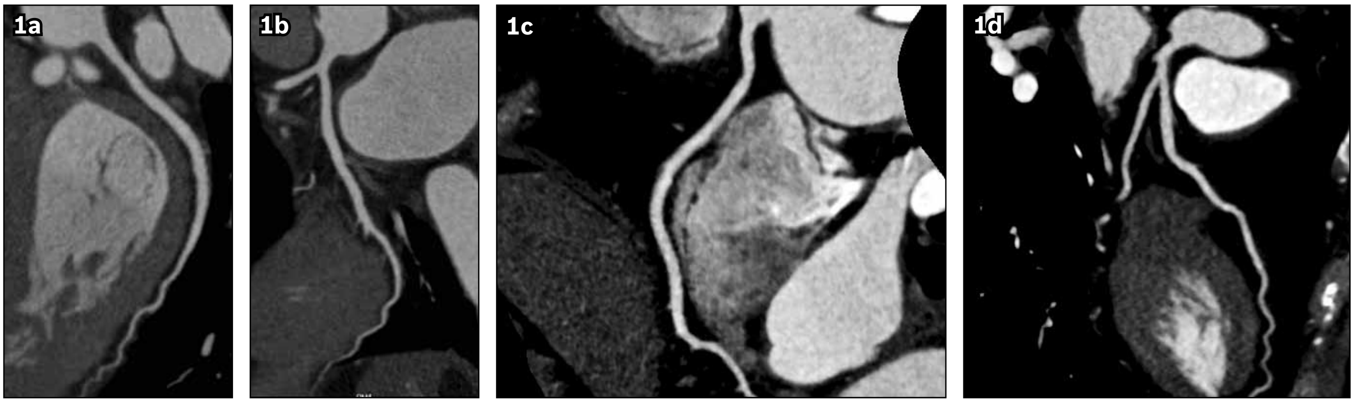


Fig. 1 Prospective ECG-triggered CCTA with curved planar reformatted images show (a) the right coronary artery and (b) branches of the left coronary artery with excellent vessel visualisation and no artefacts. Retrospective ECG-gated CCTA images in another patient show normal (c) right and (d) left coronary arteries.

A formal consensus method based on the Quality Assessment of Diagnostic Accuracy Studies (QUADAS) was used by an investigator for quality assessments of the diagnostic accuracy of the studies identified (Table I). QUADAS is regarded as an important tool for the quality assessment of systematic reviews, as it enables the development and evaluation of evidence-based quality of individual studies in terms of the potential for bias, lack of applicability and quality of reporting.(13)

Data extraction and analysis

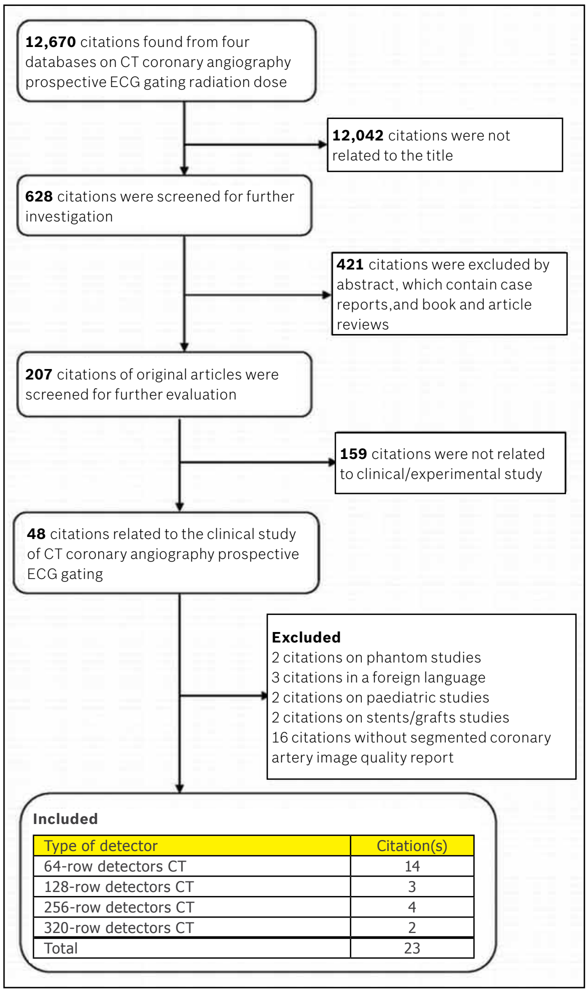
The data were recorded and extracted independently by two authors based on the selection criteria. Any disagreements on the final results were resolved by consensus. Data extraction, which was performed individually for each article, included: (a) year of publication; (b) type of scanner (64-, 128-, 256- or 320-slice CT) used; (c) technical parameters such as beam collimation, gantry rotation time, exposure factors and temporal resolution; and (d) patient demographics such as number of patients, age, body mass index (BMI) and heart rate. The effective dose was recorded for each study as a variable in our review. Effective doses were calculated from the data available in the original reports. Calculations were based on dose-length product (DLP), which was obtained from the CT scanning protocol of each CCTA study. DLP was multiplied with a conversion coefficient factor (CC), which was 0.014 or 0.017 mSv.mGy-1.cm-1, based on the average of the male and female anatomical phantoms.(14,15)

The quantitative and qualitative assessments of diagnostic image quality recorded in each study were analysed. Information regarding image quality assessments was analysed for four different manufacturers (Siemens, Philips, Toshiba and GE) and various types of scanners (64-, 128-, 256- and 320-slice CT). Quantitative image quality was determined by measuring signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR) for comparisons among the studies. SNR was calculated as the mean Hounsfield unit (HU) of a particular region of interest divided by the image noise. CNR was defined as the difference of attenuation values between contrast enhancements at two different regions (e.g. left ventricular chamber and left ventricular wall) divided by the image noise. Image noise was defined as the standard deviation (SD) of HU measured at the selected anatomical region.

Table I. Quality Assessment of Diagnostic Accuracy Studies.

Item	Description
1	Was the spectrum of patients representative of patients who will receive the test in practice?
2	Was the selection criteria clearly described?
3	Is the reference standard likely to correctly classify the target condition?
4	Is the time period between the reference standard and index test short enough to be reasonably sure that the target condition did not change between the two tests?
5	Did the whole sample or a random selection of the sample receive verification using a reference standard of diagnosis?
6	Did patients receive the same reference standard regardless of the index test results?
7	Was the reference standard independent of the index test (i.e. the index test did not form part of the reference standard)?
8	Was the execution of the index test described in sufficient detail to permit replication of the test?
9	Was the execution of the reference standard described in sufficient detail to permit its replication?
10	Were the index test results interpreted without knowledge of the results of the reference standard?
11	Were the reference standard results interpreted without knowledge of the results of the index test?
12	Were the same clinical data available when test results were interpreted as would be available when the test was used in practice?
13	Were uninterpretable/intermediate test results reported?
14	Were withdrawals from the study explained?

Qualitative assessment of image quality was carried out on a per-segment basis using a 3–5-point Likert rank-scale. The coronary segments were analysed, and the results were documented and categorised in terms of the percentage of assessable and nonassessable coronary segments. Coronary segments were subsequently classified based on the descriptions of each score in the Likert rank-scales of the original studies. The coronary arteries were characterised into 15–19 segments according to the classification of the American Heart Association (AHA).(16) The extent of stenosis was evaluated in each segment, and > 50%



Type of detector	Citation(s)
64-row detectors CT	14
128-row detectors CT	3
256-row detectors CT	4
320-row detectors CT	2
Total	23

Fig. 2 Flow chart shows the search strategy employed to identify eligible studies.

coronary stenosis was defined as significant. The sensitivity, specificity, positive predictive value (PPV), NPV and diagnostic accuracy for the detection of significant coronary stenosis were also analysed.

Statistical analysis

Data were analysed using the Statistical Package for the Social Sciences for Windows version 19.0 (SPSS Inc, Chicago, IL, USA). The assessment of image quality for each study was extracted and analysed using analysis of variance (ANOVA) for multifactorial mean comparisons. The radiation dose was also compared between the scanner types (dual source vs. single source 64-, 128-, 256- and 320-slice CT) using ANOVA. A p-value of < 0.05 was considered statistically significant.

RESULTS

Our search of the abovementioned databases identified 12,670 studies, out of which 23 articles met the selection criteria and were included in the analysis (Table II).(2,5-9,14,17-32) The attrition diagram for our study depicting the search process is shown in Fig. 2. A total of 2,080 patients were included in the 23 studies selected. The median age of the patients was 59 (range 45–70) years. The average heart rate of patients who underwent CCTA with prospective ECG triggering was 60.8 beats per minutes (bpm; 95% confidence interval [CI] 54.6–82.8), while the BMI was 25.3 kg/m^2 (95% CI 22.3–28.0). The findings of quality assessment evaluations of the selected studies based on the QUADAS checklist are presented in Table III.

Systematic review of image quality associated with prospective ECG-triggered CCTA

Quantitative image assessments were performed in only four of the 23 studies selected.(9,19,26,27) The mean SNR of these four studies was 20.9 (95% CI 11.7–28.6) while the mean CNR was 18.0 (95% CI 5.2–22.2). There was no significant difference between the SNR and CNR values of these studies. SNR and CNR were measured at the proximal segment of the right coronary artery and in the left main coronary artery, left ventricular wall and left ventricular chamber,(19) the root of the ascending aorta,(27) ascending aorta, pulmonary artery and coronary arteries,(26) and ascending aorta and perivascular fatty tissue.(9)

Qualitative image quality evaluations could not be analysed due to the limited number of studies that provided relevant information. Only one study used a single viewer for image quality evaluations.(20) Among the other 22 studies, 15 assessed interobserver agreement using the Cohen's kappa statistic (mean 0.8, 95% CI 0.6–0.9), indicating excellent agreement between two viewers in these studies.(2,7-9,19,23-32) Two studies used consensus reading.(21,22) However, pertinent information was not available in the remaining five studies that met our selection criteria.(5,6,14,17,18)

A Likert rank-scale point score system was used in all studies to indicate the evaluability of the coronary segment. Two studies were conducted using a three-point scoring system,(14,17) which indicated image quality in terms of 'excellent', 'moderate' and 'poor' (Fig. 3). Two other studies employed a five-point scoring scale to describe image quality, but defined these five points variously.(8,26) Hosch et al described image quality as 'excellent', 'good', 'moderate', 'poor' and 'extremely poor',(8) while Muenzel et al defined the same in terms of 'excellent quality', 'good quality', 'mild artefacts', 'severe artefacts' and 'non-evaluable' (Fig. 4).(26) The remaining 19 studies used a four-point scoring system that described image quality as 'excellent', 'good', 'moderate' and 'poor' (Fig. 5). The distribution of each coronary segment is presented in Fig. 3. The coronary segments were all analysed and classified into two broad groups – assessable vs. nonassessable segments – based on their respective score descriptions in the face of these studies using different scoring systems.

A total of 26,620 coronary artery segments were evaluated in the 23 studies selected. Overall, a mean percentage of 96.8% (95% CI 83.0–100.0) of segments were assessable, while 3.2% were nonassessable (Table IV). There was no statistically significant difference in the mean percentage of assessable coronary segments among the various types of scanners used (p = 0.76). The mean percentage of assessable coronary segments in studies using 64-slice single-source CT (SSCT) and dual-source

Table II. Details of studies using prospective ECG-gated CCTA that met the selection criteria.

Study (yr)	No. of detector collimations	No. of patients	Age (yrs)	Heart rate (bpm)	BMI (kg/m²)	Tube voltage (kVp)	Effective dose (mSv)	Model/manufacturer
Achenbach et al (2010)(7)	2 × 64 × 0.6	50	NA	68 ± 9	NA	100	0.9 ± 0.1	Somatom Definition Flash/Siemens
Arnoldi et al (2009)(17)	2 × 32 × 0.6	20	58 ± 10	64 ± 9	23 ± 4	120	3.0 ± 1.0	Somatom Definition/ Siemens
Buechel et al (2011)(18)	64 × 0.625	612	59 ± 12	62	26 ± 5	100–120	1.8 ± 0.6	LightSpeed VCT XT/ GE
Carrascosa et al (2010)(19)	64 × 0.625	50	62.4 ± 12.5	54.9 ± 6.8	27.7 ± 3.4	120	3.4 ± 0.4	Brilliance CT/Philips
Chen et al (2010)(20)	2 × 128 × 0.625	10	60.0 ± 6.5	58.7 ± 6.3	23.0 ± 1.5	120	4.7 ± 0.4*	Brilliance iCT/Philips
	2 × 128 × 0.625	10	54.8 ± 8.7	56.6 ± 5.0	23.1 ± 2.1	120	2.8 ± 0.4	Brilliance iCT/Philips
Duarte et al (2011)(21)	2 × 64 × 0.6	40	62 ± 7	60 ± 5	NA	100–120	2.1 ± 0.9	Somatom Definition Flash/ Siemens
Efstathopoulos et al (2009)(6)	2 × 128 × 0.625	15	55.2 ± 7.8	57.1 ± 7.2	27.8 ± 4.3	120	3.2 ± 0.6	Brilliance iCT/Philips
Esposito et al (2012)(14)	64 × 0.625	90	61 ± 12	59 ± 7	26 ± 4	100–140	4–5.2	LightSpeed VCT XT/ GE
Feng et al (2010)(27)	2 × 64 × 0.6	31	60 ± 9	67.5 ± 9.7	24.7 ± 3.0	100	2.7 ± 0.7	Somatom Definition Flash/ Siemens
Gutstein et al (2008)(22)	2 × 32 × 0.6	42	53 ± 12	57.8 ± 4.0	24.9 ± 3.1	100–120	2.2 ± 0.8	Somatom Definition/ Siemens
Hirai et al (2008)(23)	64 × 0.625	62	65 ± 11	57.1 ± 7.8	NA	120	4.1 ± 1.8	LightSpeed VCT XT/ GE
Hosch et al (2011)(8)	2 × 128 × 0.625	115	NA	58 ± 7	NA	120	3.1 ± 0.4	Brilliance iCT/Philips
Ko et al (2010)(24)	64 × 0.625	84	55.9 ± 10.7	56.5 ± 4.3	23.8 ± 1.5	120	3.4 ± 0.6	LightSpeed VCT XT/ GE
Lu et al (2011)(25)	2 × 32 × 0.6	62	55.7 ± 9.7	67.7 ± 10.5	25.3 ± 3.0	120	3.0 ± 1.4	Somatom Definition/ Siemens
Maruyama et al (2008)(5)	64 × 0.625	76	69.9 ± 9.9	54.6 ± 6.9	23.9 ± 4.6	120	4.3 ± 1.3	LightSpeed VCT XT/ GE
Muenzel et al (2012)(26)	2 × 128 × 0.625	29	59.8	62.5 ± 15.9	25.4 ± 4.0	120	4.8†	Brilliance iCT/Philips
	2 × 128 × 0.625	24	65.2	66.6 ± 14.6	25.2 ± 2.9	120	3.9‡	Brilliance iCT/Philips
Pontone et al (2009)(2)	64 × 0.625	80	64.8 ± 9.6	54.7 ± 5.2	27.0 ± 3.9	120	5.7 ± 1.5	LightSpeed VCT XT/ GE
Qin et al (2011)(28)	320 × 0.5	240	45 ± 20	56 ± 8	NA	120	3.3 ± 2.0	Aquilion ONE/ Toshiba
Shuman et al (2008)(29)	64 × 0.625	50	NA	NA	NA	100–120	6.2 ± 2.0	LightSpeed VCT XT/ GE
Shuman et al (2009)(30)	64 × 0.625	31	55 ± 8	59 ± 6	28 ± 5	100–120	9.2 ± 2.2	LightSpeed VCT XT/ GE
Stolzmann et al (2011)(31)	2 × 32 × 0.6	100	68 ± 8	58 ± 7	26.3 ± 3.1	100–120	2.2 ± 0.4	Somatom Definition/ Siemens
Xu et al (2010)(32)	2 × 32 × 0.6	50	54.6 ± 10.1	82.8 ± 9.3	NA	100–120	5.1 ± 1.6	Somatom Definition/ Siemens
Zhang et al (2011)(9)	320 × 0.5	40	59.4 ± 10.8	55.1 ± 5.3	22.3 ± 1.5	100	2.1 ± 0.2	Aquilion ONE/ Toshiba
	320 × 0.5		56.0 ± 10.3	66.2 ± 6.6	27.8 ± 2.7	120	4.6 ± 0.8	Aquilion ONE/ Toshiba

*Additional padding windows. †FOV > 250 mm. ‡FOV < 250 mm.
bpm: beats per minute; BMI: body mass index; FOV: field of view; NA: not available

CT (DSCT) scanners were 96.5% (95% CI 88.2–99.5) and 97.5% (95% CI 92.3–99.7), respectively. The mean percentage of assessable coronary segments for 128-, 256- and 320-slice CT scanners were 97.9% (95% CI 95.0–99.5), 95.6% (95% CI 83.0–100.0) and 98.9% (95% CI 98.2–100.0), respectively.

Of the 23 studies analysed, information pertaining to the evaluation of sensitivity, specificity, PPV, NPV and accuracy for coronary artery stenosis was available in five studies.(2,5,19,25,31) Pooled estimates were determined in these five studies for patient-based assessments (sensitivity 98.3% [95% CI 96.0–100.0];

Table III. Assessment of the literature based on the Quality Assessment of Diagnostic Accuracy Studies (QUADAS).

Study (yr)	QUADAS item													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Achenbach et al (2010)(7)	Yes	Yes	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Arnoldi et al (2009)(17)	Yes	Yes	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Buechel et al (2011)(18)	Yes	Yes	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Carrascosa et al (2010)(19)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unclear	Unclear	Yes	Yes	Yes	Yes	Yes
Chen et al (2010)(20)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unclear	Unclear	Yes	Yes	Yes
Duarte et al (2011)(21)	Yes	Yes	Yes	Unclear	Yes	Yes	Yes	Unclear	Unclear	Yes	Yes	Yes	Yes	Yes
Efstathopoulos et al (2009)(6)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unclear	Unclear	Yes	Yes	Yes	Yes	Yes
Esposito et al (2012)(14)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Feng et al (2010)(27)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes
Gutstein et al (2008)(22)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Hirai et al (2008)(23)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Hosch et al (2011)(8)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Ko et al (2010)(24)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Lu et al (2011)(25)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unclear	Unclear	Yes	Yes	Yes
Maruyama et al (2008)(5)	Yes	Yes	Yes	Yes	Unclear	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Muenzel et al (2012)(26)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Pontone et al (2009)(2)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Qin et al (2011)(28)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unclear	Unclear	Yes	Yes	Yes
Shuman et al (2008)(29)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Unclear	Unclear	Yes	Yes	Yes
Shuman et al (2009)(30)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Stolzmann et al (2011)(31)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Xu et al (2010)(32)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Zhang et al (2011)(9)	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

specificity 90.5% [95% CI 85.7–96.0]; PPV 92.3% [95% CI 77.0–99.0]; NPV 90% [95% CI 75.0–100.0]; accuracy 96.2% [95% CI 95.0–98.0]), segment-based assessments (sensitivity 89.8% [95% CI 76.6–98.0]; specificity 97.2% [95% CI 95.0–98.5]; PPV 89.8% [95% CI 85.5–96.0]; NPV 92.8% [95% CI 83.0–100.0]; accuracy 95.0% [95% CI 93.0–98.0]) and vessel-based assessments (sensitivity 89.3% [95% CI 79.6–99.0]; specificity 94.7% [95% CI 92.3–97.0]; PPV 91.6% [95% CI 88.2–95.0]; NPV 92.6% [95% CI 86.2–99.0]; accuracy 92.3% [95% CI 86.6–98.0]).

Among the eight studies that assessed stenosis, three studies investigated the degree of stenosis. In these three studies, the pooled estimate of the prevalence of lesions was 79.1% (95% CI 55.0–94.4) and 11.2% (95% CI 5.6–16.0), respectively, for 50%–75% stenosis and > 75% occlusion.(18,19,23) The remaining

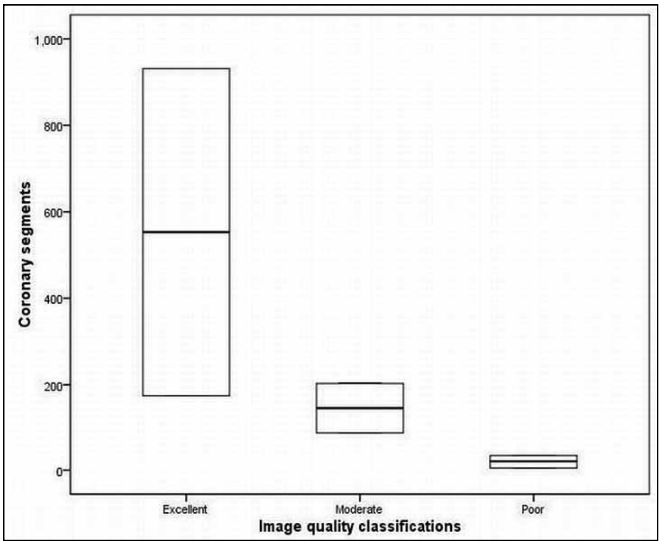


Fig. 3 Box plot shows the number of coronary segments assessed in studies on CCTA with prospective ECG gating that used a three-point scoring system to evaluate image quality (n = 2).

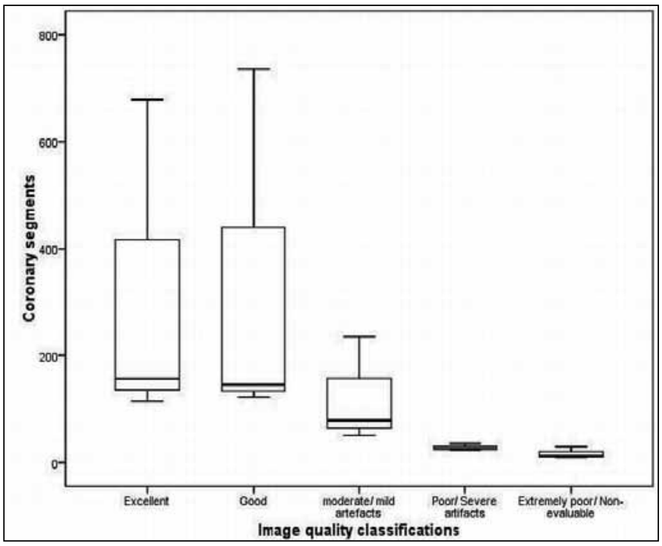


Fig. 4 Box plot shows the number of coronary segments assessed in studies on CCTA with prospective ECG gating that used a five-point scoring system to evaluate image quality (n = 2).

five studies focused on the location of stenosis and coronary vessel involvement.(7,19,22,26,31) A comparison of data could not be performed among these five studies, as they used divergent methods of analysis, although the sensitivities for detecting stenosis on vessel-based (sensitivity 89.3%) and segment-based (sensitivity 89.8%) assessments were found to be lower than that on patient-based assessment (sensitivity 98.3%).

Systematic review of radiation dose associated with prospective ECG-triggered CCTA

The overall mean DLP was 224.8 mGy.cm (95% CI 183.6–265.9) for 21 studies performed with prospective ECG-triggered CCTA.(2,5-9,17-26,28-32) DLP values were not provided in the remaining two studies.(14,27) A wide variation was observed in the mean DLP values obtained from the various types of CT scanners (64-slice SSCT 283.7 mGy.cm [95% CI 222.5–345.1]; DSCT 147.9 mGy.cm [95% CI 107.3–188.5]; 128-slice CT 134.4 mGy.cm [95% CI 91–184]; 256-slice CT 234 mGy.cm [95% CI 186.7–281.2]; 320-slice CT 196.6 mGy.cm [95% CI 167–228]). The mean DLP acquired with DSCT was significantly lower than that obtained with 64-slice SSCT and 256-slice CT ($p < 0.05$). Similarly, the mean DLP acquired with 128-slice CT was significantly lower than that obtained with 64-slice SSCT and 256-slice CT ($p < 0.05$).

The overall mean effective dose was 3.6 mSv (95% CI 2.9–4.3) in the 23 studies performed with prospective ECG-triggered CCTA (64-slice SSCT 4.7 mSv [95% CI 3.0–6.3]; DSCT 3.1 mSv [95% CI 1.6–4.5]; 128-slice CT 1.9 mSv [95% CI 0.9–2.7]; 256-slice CT 3.7 mSv [95% CI 2.8–4.6]; 320-slice CT 3.3 mSv [95% CI 2.1–4.6]). The lowest effective dose was found in prospective ECG-triggered CCTA performed with 128-slice CT, which was significantly lower than that acquired with 64-slice SSCT and 256-slice CT ($p < 0.05$). The mean effective dose acquired with DSCT was significantly lower than that obtained with 64-slice SSCT ($p < 0.05$). The mean effective dose (3.8 mSv; 95% CI 2.9–5.6) was higher in patients with BMI > 25 kg/m^2 than those with BMI < 25 kg/m^2 (3.1 mSv; 95% CI 2.3–3.9). However, there was no statistically significant difference between these two groups of patients ($p > 0.05$).

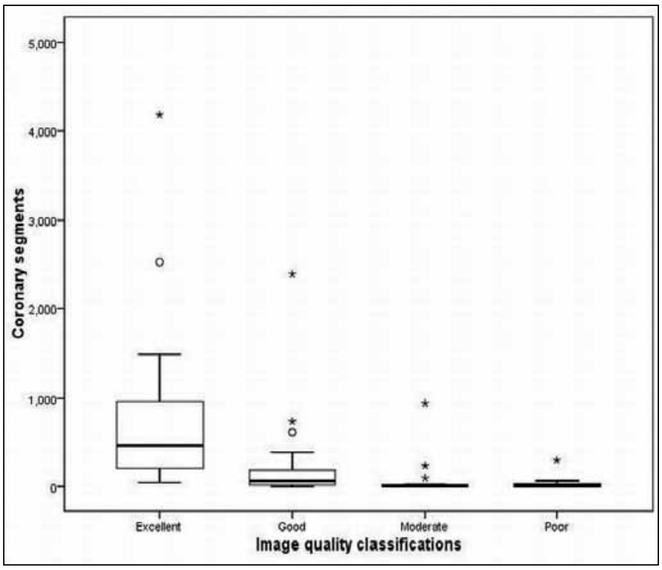


Fig. 5 Box plot shows the number of coronary segments assessed in studies on CCTA with prospective ECG gating that used a four-point scoring system to evaluate image quality (n = 19).

Several techniques were found to have been introduced in some studies to further reduce radiation doses. One study was conducted with high pitch values so that the effective dose was less than 1.0 mSv.(7) In other studies, applying a high field of view (FOV > 250 mm, 4.8 mSv vs. FOV < 250 mm, 3.9 mSv)(26) and lowering the tube voltage to 100 kVp (100 kVp, 2.7 mSv vs. 120 kVp, 3.9 mSv)(7,9,14,18,21,22,29-32) led to reductions in radiation doses.

DISCUSSION

Our analysis highlights two findings that are of considerable importance for the clinical application of CCTA with prospective

Table IV. Analysis of coronary artery segments (n = 26,620) in studies using prospective ECG-gated CCTA.

Study (yr)	Segment classifications used	No. of segments involved	Segment diameter requirement	Assessable segments (%)
Achenbach et al (2010)(7)	18	742	All segments	99.5
Arnoldi et al (2009)(17)	15	269	All segments	98.1
Buechel et al (2011)(18)	16	7,814	> 1.5 mm	96.2
Carrascosa et al (2010)(19)	17	51	> 1.5 mm	88.2
Chen et al (2010)(20)	15	138	NA*	100
	15	160	NA	100
Duarte et al (2011)(21)	16	450	> 1.5 mm	99.1
Efstathopoulos et al (2009)(6)	16	224	All segments	83.0
Esposito et al (2012)(14)	16	1,170	All segments	96.9
Feng et al (2010)(27)	NS	439	NA	95.0
Gutstein et al (2008)(22)	15	633	NA	99.2
Hirai et al (2008)(23)	17	828	> 1.5 mm	98.7
Hosch et al (2011)(8)	15	1,714	All segments	96.3
Ko et al (2010)(24)	16	1,226	> 1.5 mm	97.4
Lu et al (2011)(25)	15	246	All segments	92.3
Maruyama et al (2008)(5)	15	1,089	All segments	96.7
Muenzel et al (2012)(26)	16	390	> 1.0 mm†	97.2
	16	294	> 1.0 mm‡	96.9
Pontone et al (2009)(2)	15	1,044	> 1.5 mm	95.6
Qin et al (2011)(28)	15	3,240	> 1.5 mm	100
Shuman et al (2008)(29)	19	614	> 1.5 mm	98.9
Shuman et al (2009)(30)	19	394	> 1.5 mm	99.5
Stolzmann et al (2011)(31)	16	1,508	> 1.0 mm	98.4
Xu et al (2010)(32)	16	610	> 1.5 mm	99.7
Zhang et al (2011)(9)	16	504	> 1.5 mm§	98.2
	16	829	> 1.5 mm‖	98.6

*Additional padding window. †FOV > 250 mm. ‡FOV < 250 mm. §100 kVp. ‖120 kVp
NA: not available; FOV: field of view

ECG gating in patients with CAD. Firstly, our review found that a high percentage of assessable coronary segments was achieved regardless of the type of scanners used. Secondly, prospective ECG-gated CCTA demonstrated high sensitivity, specificity, NPV, PPV and accuracy for detecting CAD while achieving significantly lower radiation doses.

In this review, an evaluation of the subjective image quality assessments of the studies analysed found that 96.8% of the coronary segments were assessable and the number of nonassessable segments reported with prospective ECG-gated CCTA was very small. This finding may indicate that targeting patients with appropriate heart rates depending on the type of scanner and scanning technique being used in a study might help to reduce the rejection of coronary segments.

Beta-blockage is routinely recommended as a prerequisite prior to scanning in order to lower heart rates and improve diagnostic image quality,(33) as heart rate is a key factor in determining image quality. For instance, Ko et al reported recently that the percentage of nonassessable coronary images increased significantly with heart rate > 57 bpm and heart rate variability > 6 bpm.(24) On the other hand, according to Xu et al, image quality acquired using DSCT with prospective ECG gating was diagnostic even in patients with heart rates > 65 bpm.(32) Similarly, a meta-analysis of 24 studies showed that DSCT coronary angiography had high sensitivity and specificity for CAD, especially in patients with high heart rates.(34) Our results were consistent with these reports, as we too found that assessable segments in studies using DSCT coronary angiography were higher than those in studies using SSCT coronary angiography, although the difference was not statistically significant.

Prospective ECG-triggered CCTA using DSCT was performed in half of the studies analysed and included patients with heart rates > 65 bpm. However, in studies that used other types of multislice CT scanners (64-, 256- or 320-slice), patients' heart rates were < 65 bpm in nearly 90% of the reports. DSCT improves temporal resolution to 83 msec (75 msec for second generation of DSCT), which is vital in patients who have contraindications for β-blockers. Further studies comparing DSCT with SSCT coronary angiography using prospective ECG gating will be required to confirm the diagnostic accuracy of DSCT.

In response to the general concern for the high doses of radiation associated with CCTA, various dose-saving strategies were found to have been introduced in the literature, with the aim of reducing radiation dose while still preserving the diagnostic value of CCTA for CAD.(2) Among the various dose-saving strategies proposed, prospective ECG triggering represents the most recent approach that has accounted for a significant reduction in radiation dosage when compared to conventional retrospective ECG gating.(3,35-37) Although the present analysis did not focus on studies using retrospective ECG-gated CCTA, radiation dose reports from previous studies confirm that effective doses were significantly reduced by prospective ECG gating (3.6 mSv) when compared to retrospective ECG gating (18–24 mSv).(23,38) Several other studies on radiation doses also indicate that prospective ECG-gated CCTA leads to a dose reduction of up to 83% when compared to retrospective ECG gating.(25,29,39,40) We found that the effective dose in studies on prospective ECG-gated CCTA was even lower than that reported in a previous study on invasive coronary angiography (5.6 mSv).(41) Application of high pitch values and lower tube voltages during prospective ECG-gated CCTA could further reduce radiation dose to < 1 mSv.(7,42)

We found that DLP was a more objective measure for characterising studies on CCTA than effective dose, as the variability observed in DLPs from different studies was striking. Median DLP in studies with the highest doses was over two times that in studies with the lowest doses. This was especially apparent in 64-slice SSCT studies, where CT doses were in the range of 130–541 mGy.cm. CCTA may therefore be associated with a significantly higher or lower effective dose than standard invasive coronary angiography, depending on how CCTA is performed. DLP represents most closely the radiation dose received by an individual patient, and for that reason, may be used to set reference values for a given type of CT examination in order to ensure that patient doses during the procedure are as low as practically possible. We recommend that DLP be recorded for each study on CCTA and serve as the cornerstone of all quality assurance efforts.(43)

The principle behind prospective ECG triggering is that data acquisition only takes place during the selected cardiac phase, where the X-ray tube is only selectively turned on when triggered by an ECG signal and turned off or dramatically lowered during the rest of the R-R cycle. This technique is limited to heart rates < 70 bpm or 65 bpm. In addition, ECG-triggered sequential scans are usually restricted to scanning with nonoverlapping adjacent slices or slice increments with only small overlaps. The scan time needed to cover the heart volume is thus directly proportional to the slice increment. Consequently, as prospective ECG triggering places high demand on the z-axis coverage, it is usually performed using 64-slice or higher slice scanners. The presence of misalignment due to image acquisition occurring over the 4–5 heart beats that are needed to cover the entire heart using 64-slice CT is an example of this limitation. This shortcoming can be overcome using the latest 320-slice CT scanners that can cover the cardiac volume in a single heartbeat.(44)

Some limitations exist in this review. Firstly, all the studies analysed lacked objective assessment. Only 17% (4/23) of the studies provided details on quantitative assessment of image quality. In contrast, subjective image analyses were reported in all the studies. Our selection criterion that every study necessarily provides a subjective image quality assessment limited the number of studies that could be included in our review. As a single viewer conducted image quality assessment in one study, it is possible that the evaluation of image quality in this study might have been subject to some bias, and this may have implications on the scoring of coronary artery segments in our analysis. However, image quality assessments in a majority of studies (96%) were performed by two viewers with good interobserver agreement. Secondly, limited information was available on diagnostic accuracy in our analysis. We suggest that investigations of the diagnostic value of prospective ECG triggering be conducted in future studies with large patient populations. Finally, publication bias may have played a role in our results, as only articles in the English literature were included in our study.

In conclusion, this systematic review shows that prospective ECG-triggered CCTA provides high diagnostic image quality with high diagnostic accuracy for detecting coronary artery stenosis. Prospective ECG-triggered CCTA protocols produce a significantly lower radiation dose compared to retrospective ECG-gated CCTA.

REFERENCES

1. Sun Z, Lin C, Davidson R, Dong C, Liao Y. Diagnostic value of 64-slice CT angiography in coronary artery disease: a systematic review. Eur J Radiol 2008; 67:78-84.
2. Pontone G, Andreini D, Bartorelli AL, et al. Diagnostic accuracy of coronary computed tomography angiography: a comparison between prospective and retrospective electrocardiogram triggering. J Am Coll Cardiol 2009; 54:346-55.
3. Sun Z, Ng KH. Prospective versus retrospective ECG-gated multislice CT coronary angiography: A systematic review of radiation dose and diagnostic accuracy. Eur J Radiol 2012; 81:e94-e100.
4. Van Mieghem CA, Cademartiri F, Mollet NR, et al. Multislice spiral computed tomography for the evaluation of stent patency after left main coronary artery stenting: a comparison with conventional coronary angiography and intravascular ultrasound. Circulation 2006; 114:645-53.
5. Maruyama T, Takada M, Hasuike T, et al. Radiation dose reduction and coronary assessability of prospective electrocardiogram-gated computed tomography coronary angiography: comparison with retrospective electrocardiogram-gated helical scan. J Am Coll Cardiol 2008; 52:1450-5.
6. Efstathopoulos EP, Kelekis NL, Pantos I, et al. Reduction of the estimated radiation dose and associated patient risk with prospective ECG-gated 256-slice CT coronary angiography. Phys Med Biol 2009; 54:5209-22.
7. Achenbach S, Marwan M, Ropers D, et al. Coronary computed tomography angiography with a consistent dose below 1mSv using prospectively electrocardiogram-triggered high-pitch spiral acquisition. Eur Heart J 2010; 31:340-6.
8. Hosch W, Heye T, Schulz F, et al. Image quality and radiation dose in 256-slice cardiac computed tomography: Comparison of prospective versus retrospective image acquisition protocols. Eur J Radiol 2011; 80:127-35.
9. Zhang C, Zhang Z, Yan Z, et al. 320-row CT coronary angiography: effect of 100-kV tube voltages on image quality, contrast volume, and radiation dose. Int J Cardiovasc Imaging 2011; 27:1059-68.
10. Klass O, Walker M, Siebach A, et al. Prospectively gated axial CT coronary angiography: comparison of image quality and effective radiation dose between 64- and 256-slice CT. Eur Radiol 2010; 20:1124-31.

11. De France T, Dubois E, Gebow D, et al. Helical prospective ECG-gating in cardiac computed tomography: radiation dose and image quality. Int J Cardiovasc Imaging 2010; 26:99-107.
12. Weigold WG, Olszeewski ME, Walker MJ. Low-dose prospectively gated 256-slice coronary computed tomographic angiography. Int J Cardiovasc Imaging 2009; 25 suppl 2:217-30.
13. Whiting P, Rutjes AW, Reitsma JB, Bossuyt PM, Kleijnen J. The development of QUADAS: a tool for the quality assessment of studies of diagnostic accuracy included in systematic reviews. BMC Med Res Methodol [online] 2003; 3:25. Available at: www.biomedcentral.com/1471-2288/3/25. Accessed November 11, 2011.
14. Esposito A, De Cobelli F, Colantoni C, et al. Gender influence on dose saving allowed by prospective-triggered 64-slice multidetector computed tomography coronary angiography as compared with retrospective-gated mode. Int J Cardiol 2012; 158:253-9.
15. Huda W, Ogden KM, Khorasani MR. Converting dose-length product to effective dose at CT. Radiology 2008; 248:995-1003.
16. Austen WG, Edwards JE, Frye RL, et al. A reporting system on patients evaluated for coronary artery disease. Report of the Ad Hoc Committee for Grading of Coronary Artery Disease, Council on Cardiovascular Surgery, American Heart Association. Circulation 1975; 51(4 Suppl):5-40.
17. Arnoldi E, Johnson TR, Rist C, et al. Adequate image quality with reduced radiation dose in prospectively triggered coronary CTA compared with retrospective techniques. Eur Radiol 2009; 19:2147-55.
18. Buechel RR, Husmann L, Herzog BA, et al. Low-dose computed tomography coronary angiography with prospective electrocardiogram triggering: feasibility in a large population. J Am Coll Cardiol 2011; 57:332-6.
19. Carrascosa P, Capunay C, Deviggiano A, et al. Accuracy of low-dose prospectively gated axial coronary CT angiography for the assessment of coronary artery stenosis in patients with stable heart rate. J Cardiovasc Comput Tomogr 2010; 4:197-205.
20. Chen LK, Wu TH, Yang CC, Tsai CJ, Lee JJ. Radiation dose to patients and image quality evaluation from coronary 256-slice computed tomographic angiography. Nucl Instrum Methods Phys Res A 2010; 619:368-71.
21. Duarte R, Fernandez G, Castellon D, Costa JC. Prospective coronary CT angiography 128-MDCT versus retrospective 64-MDCT: improved image quality and reduced radiation dose. Heart Lung Circ 2011; 20:119-25.
22. Gutstein A, Wolak A, Lee C, et al. Predicting success of prospective and retrospective gating with dual-source coronary computed tomography angiography: development of selection criteria and initial experience. J Cardiovasc Comput Tomogr 2008; 2:81-90.
23. Hirai N, Horiguchi J, Fujioka C, et al. Prospective versus retrospective ECG-gated 64-detector coronary CT angiography: assessment of image quality, stenosis, and radiation dose. Radiology 2008; 248:424-30.
24. Ko SM, Kim NR, Kim DH, Song MG, Kim JH. Assessment of image quality and radiation dose in prospective ECG-triggered coronary CT angiography compared with retrospective ECG-gated coronary CT angiography. Int J Cardiovasc Imaging 2010; 26:93-101.
25. Lu B, Lu JG, Sun ML, et al. Comparison of diagnostic accuracy and radiation dose between prospective triggering and retrospective gated coronary angiography by dual-source computed tomography. Am J Cardiol 2011; 107:1278-84.
26. Muenzel D, Noel PB, Dorn F, et al. Coronary CT angiography in step-and-shoot technique with 256-slice CT: Impact of the field of view on image quality, craniocaudal coverage, and radiation exposure. Eur J Radiol 2012; 81:1562-8.
27. Feng Q, Yin Y, Hua X, et al. Prospective ECG triggering versus low-dose retrospective ECG-gated 128-channel CT coronary angiography: comparison of image quality and radiation dose. Clin Radiol 2010; 65:809-14.
28. Qin J, Liu LY, Meng XC, et al. Prospective versus retrospective ECG gating for 320-detector CT of the coronary arteries: comparison of image quality and patient radiation dose. Clin Imaging 2011; 35:193-7.
29. Shuman WP, Branch KR, May JM, et al. Prospective versus retrospective ECG gating for 64-detector CT of the coronary arteries: comparison of image quality and patient radiation dose. Radiology 2008; 248:431-7.
30. Shuman WP, Branch KR, May JM, et al. 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. AJR Am J Roentgenol 2009; 192:1662-7.
31. Stolzmann P, Goetti R, Baumueller S, et al. Prospective and retrospective ECG-gating for CT coronary angiography perform similarly accurate at low heart rates. Eur J Radiol 2011; 79:85-91.
32. Xu L, Yang L, Zhang Z, et al. Low-dose adaptive sequential scan for dual-source CT coronary angiography in patients with high heart rate: Comparison with retrospective ECG gating. Eur J Radiol 2010; 76:183-7.
33. Pannu HK, Alvarez W, Fishman EK. β-blockers for cardiac CT: a primer for the radiologist. Am J Roentgenol 2006; 186:S341-5.
34. Guo SL, Guo YM, Zhai YN, et al. Diagnostic accuracy of first generation dual-source computed tomography in the assessment of coronary artery disease: a meta-analysis from 24 studies. Int J Cardiovasc Imaging 2011; 27:755-71.
35. Sun Z. Multislice CT angiography in cardiac imaging: prospective ECG-gating or retrospective ECG-gating? Biomed Imaging Interv J 2010; 6:e4.
36. Von Ballmoos MW, Haring B, Juillerat P, Alkadhi H. Meta-analysis: diagnostic performance of low-radiation-dose coronary computed tomography angiography. Ann Intern Med 2011; 154:413-20.
37. Sun Z, Ng KH. Diagnostic value of coronary CT angiography with prospective ECG-gating in the diagnosis of coronary artery disease: a systematic review and meta-analysis. Int J Cardiovasc Imaging 2012; 28: 2109-19.
38. Earls JP, Berman EL, Urban BA, et al. Prospectively gated transverse coronary CT angiography versus retrospectively gated helical technique: improved image quality and reduced radiation dose. Radiology 2008; 246:742-53.
39. Earls JP. How to use a prospective gated technique for cardiac CT. J Cardiovasc Comput Tomogr 2009; 3:45-51.
40. Sabarudin A, Sun Z, Ng KH. Radiation dose associated with coronary CT angiography and invasive coronary angiography: An experimental study of the effect of dose-saving strategies. Radiat Prot Dosimetry 2012; 150:180-7.
41. Coles DR, Smail MA, Negus IS, et al. Comparison of radiation doses from multislice computed tomography coronary angiography and conventional diagnostic angiography. J Am Coll Cardiol 2006; 47:1840-5.
42. Alkadhi H, Stolzmann P, Desbiolles L, et al. Low-dose, 128-slice, dual-source CT coronary angiography: accuracy and radiation dose of the high-pitch and the step-and-shoot mode. Heart 2010; 96:933-8.
43. Hendel RC, Budoff MJ, Cardella JF, et al. ACC/AHA/ACR/ASE/ASNC/HRS/NASCI/RSNA/SAIP/SCAI/SCCT/SCMR/SIR 2008 key data elements and definitions for cardiac imaging A Report of the American College of Cardiology/American Heart Association Task Force on Clinical Data Standards (Writing Committee to Develop Clinical Data Standards for Cardiac Imaging). J Am Coll Cardiol 2009; 53:91-124.
44. Hoe J, Toh KH. First experience with 320-row multidetector CT coronary angiography scanning with prospective electrocardiogram gating to reduce radiation dose. J Cardiovasc Comput Tomogr 2009; 3:257-61.