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Title: A systematic review of radiation dose associated with different generations of multidetector CT coronary angiography

Running Head: Radiation dose associated with multidetector CT coronary angiography

Authors:

Mr. Akmal Sabarudin MSc[1]

A/Prof. Zhonghua Sun PhD[1]

Prof. Kwan-Hoong Ng PhD[2]

[1] Discipline of medical Imaging, Department of Imaging and Applied Physics, Curtin University, GPO Box U1987 Perth, Western Australia 6845, Australia

[2] Department of Biomedical Imaging, University of Malaya, Kuala Lumpur, 50603, Malaysia

Corresponding author:

Associate Professor Zhonghua Sun

Discipline of Medical Imaging

Department of Imaging and Applied Physics

Curtin University

GPO Box, U1987

Perth, 6845, Australia

Phone: 08 9266 7509

Fax: 08 9266 2377

Mobile: 0415 769 139

Email: z.sun@curtin.edu.au

Abstract

Introduction: The purpose of this paper is to perform a systematic review on radiation dose reduction in coronary CT (computed tomography) angiography that is done using different generations of multidetector CT (MDCT) scanners ranging from 4-slice to 320-slice CTs, and have different dose-saving techniques.

Methods: The method followed was to search for references on coronary CT angiography (CTA) that had been published in English between 1998 and February 2011. The effective radiation dose reported in each study based on different generations of MDCT scanners was analyzed and compared between the types of scanners, gender, exposure factors and scanning protocols.

Results: Sixty-six studies were eligible for inclusion in this analysis. The mean effective dose (ED) for MDCT angiography with retrospective ECG-gating without use of any dose-saving protocol was 6.0± 2.8 mSv, 10.4 ± 4.90 mSv and 11.8 ± 5.9 mSv for 4-slice, 16-slice and 64-slice CTs, respectively. More dose-saving strategies were applied in recent CT generations including prospective ECG-gating protocols, application of lower tube voltage, and tube current modulation to achieve a noteworthy dose reduction. Prospective ECG-gating protocol was increasingly used in 64-, 125-, 256- and 320-slices with corresponding ED of 4.1 ± 1.7 mSv, 3.6 ± 0.4 mSv, 3.0 ± 1.9 mSv and 7.6 ± 1.6 mSv, respectively. Lower tube voltage and tube current modulation were widely applied in 64-slice CT and resulted in significant dose reduction ($p<0.05$). **Conclusions:** This analysis has shown that dose-saving strategies can substantially reduce the radiation dose in CT coronary angiography. The fact that more and more clinicians are opting for dose-saving strategies in CT coronary angiography indicates an increased awareness of risks associated with high radiation doses amongst them.

Keywords: coronary artery disease, coronary CT angiography, multidetector CT, radiation dose, dose reduction

Introduction

Coronary artery disease (CAD) is a common cardiovascular disease and a leading cause of death amongst people in advanced countries. Early detection and diagnosis play an important role in patient management. Traditionally, this has been achieved with use of invasive coronary angiography; however, this technique is associated with procedure-related complications. Therefore, ever since multi-detector computed tomography angiography (MDCTA) has been introduced as a non-invasive technique in cardiac imaging it has been widely used to detect CAD as a less invasive imaging modality.[1,2]

Over the last decade MDCT has undergone rapid technical developments, and has demonstrated regular technical improvements starting with the early generation of 4-slice to 16-slice, 64-slice and up till the most recent models of 320-slice scanners.[3-5] Although rapid developments in MDCT technology have led to striking improvements in both image quality and diagnostic value in cardiovascular imaging, MDCT runs the potential risk of high radiation dose.[6-9] Preliminary studies have shown that radiation dose increases with increasing detector rows in CT due to narrow detector collimations and long anatomic coverage.[10] It is generally agreed that CT is an imaging modality with high radiation exposure, as it contributes up to 70 per cent radiation dose of all radiological examinations, although it comprises only 15 per cent of all radiological examinations.[11] Recent advances and improvements to the spatial and temporal resolution of MDCT have increased its accuracy to diagnose CAD; however, this has resulted in increased radiation dose. The radiation risks associated with cardiac MDCTA have raised serious concerns in the literature.[6,10,11] Thus, the questions have to be addressed, which are: Does utilisation of cardiac MDCTA lead to the greatest benefit and is the risk of radiation greater than the benefit expected from the CT examinations?[12]

Despite the increased awareness of radiation risk, there are many clinicians and researchers who have not yet realised the amount of radiation exposure associated with coronary CTA, or the possibility of tailoring the scanning protocols to reduce radiation dose. Therefore, the aim of this study is to carry out a systematic review of radiation dose in coronary CTA performed with different generations of MDCT scanners and various dose-saving techniques based on the available literature. We expect that the research findings of this study will provide valuable information for radiologists and radiographers with regard to optimisation of radiation exposure and judicious use of MDCT in the diagnosis of CAD.

Methods

The literature search for relevant references was performed by using eight different databases, which included Highwire Press, Ovid, PubMed, ProQuest Health and Medical Complete, Medline, ScienceDirect, Scopus and SpringerLink to cover publications between 1998 (MDCT was first introduced in 1998) and 2011 (last search was done in February 2011). The terms used for identification of references were 'multidetector/multislice CT coronary angiography', 'multidetector/multislice CT coronary angiography', 'radiation dose and effective dose in multidetector CT coronary angiography', and 'dose reduction strategies for CT coronary angiography'. Each of these terms was matched separately with prefix of 4-, 16-, 40-, 64-, 128-, 256-, 320-slice CT. The search was limited to include all the studies that had been published in the English language and were on human subjects. All the retrospective/prospective studies were included in this review as long as the effective radiation dose was provided in studies using MDCTA in the diagnosis of CAD. Exclusion criteria included calcium scoring on coronary CT scans, case reports, phantom studies, and studies with use of electron beam CT. Moreover, all the references were checked manually in order to ensure the precision and originality of the review. Comparisons of effective dose in each CT generation were performed based on multiple variables including demographic characteristics and technical parameters such as exposure factors (kVp, mAs), and scanning protocols (collimation, pitch, ECG-gating).

Data were extracted by two authors (AS and ZS) independently and all disagreements were resolved through consensus. Data extraction was based on the following characteristics in each study: year of publication, number of patients included in each study, age and gender, type of CT scanner, scanning protocols and technique, gantry rotation time, beam collimation, exposure factors (kVp and mA), pitch, method of electrocardiogram (ECG) gating (retrospective or prospective gating), and strategies to reduce radiation dose (adjustment of tube voltage or tube current). Effective dose was recorded in terms of mean value and dose range corresponding to the gender. In addition, $CTDI_{vol}$ and dose length product (DLP) were checked in each study and recorded, wherever available.

Statistical analysis

All data were analyzed and processed using SPSS V 17.0 (SPSS Inc, Chicago, IL). Effective doses are expressed as mean value ± SD. Comparisons were performed using one sample two-sided T test. A p value less than 0.05 was defined as a statistically significant difference.

Results

The search process and results of obtaining these references are shown in Figure 1. Eighty-three citations were identified to be relevant to the cardiac MDCT angiography with reports of radiation dose, and only 66 articles were found to meet the selection requirements for inclusion in this review, [3-5,13-75] as shown in Figure 1. Two studies were reported from the same research group, so one study was excluded from the analysis.[76] Twelve studies were performed on 4-slice CT,[13-23,75] 13 on 16-slice CT,[24-36] 1 on 40-slice CT,[41] 23 on 64-slice CT,[5,42-63] 1 on 128-slice,[69] 5 on 256-slice,[65-68,70] and 6 on 320-slice CT,[3,4,71-74] respectively, and the remaining five studies consisted of a combination of different generations of MDCT scanners for comparative purposes. [37-40,64] Therefore, according to the individual study cases, 12 studies were performed on 4-slice CT, 17 on 16-slice, 1 on 40-slice CT, 28 on 64-slice, 3 on 128-slice, 5 on 256-slice, and 6 on 320-slice CT.

Four different manufacturers of CT scanners were used in the studies with different models. These included Siemens Medical Solution, Philips Medical System, GE Healthcare and Toshiba Corporation Medical System and are shown in Figure 2.

4- and 16-slice CT

Table 1 presents the mean effective dose (ED) associated with 4-slice CT coronary angiography in 12 studies, which is 6.0 ± 2.8 mSv. The results were analyzed with different variables such as gender, exposure parameters, and dose saving strategies. In the comparison between genders, the ED was estimated with 4.9 ± 2.5 mSv and 6.6 ± 3.1 mSv in male and female patients, respectively. However, four out of 12 studies did not specify the radiation dose in relation to the patient's gender, since only the mean ED was reported which is 7.0 ± 2.6 mSv.[18-21] Moreover, all studies were performed with retrospective ECG-gating scanning protocols of minimum 120 kVp and a pitch ranging from 0.375 to 2.0. Three out of 12 studies were performed with high pitch corresponding to the heart rate with a pitch of 1.5 used for heart rates below 80 bpm (beats per minute) and pitch 2.0 for heart rates more than 80 bpm.[16-18.]

The mean ED was estimated to be 10.4 ± 4.9 mSv in 16-slice coronary CTA with use of retrospective ECG-gating protocol. A 120 kVp protocol was consistently used in almost 90 per cent of 17 studies performed with 16-slice coronary CTA (Table 1), with beam collimation less than 1.0 mm and the mean ED being 9.6 ± 4.3 mSv, which is higher than in 4-slice CTA. A lower dose protocol with 100 kVp was implemented in two studies,[35,38] and the mean ED was 6.4 ± 1.9 mSv, indicating a dose reduction of up to 33 per cent. Another effective approach for dose reduction called ECG-controlled tube current modulation was applied in six out of 17 studies. This was done to compare it with the conventional retrospective ECG-gating scan without use of tube current modulation. The analysis shows that ED in a scan protocol with application of tube current modulation was significantly lower (6.7 ± 1.8 mSv) than without using tube current modulation (11.6 ± 5.1 mSv) ($p<0.01$).

Another aspect that could increase radiation dose is an extension of the scanning region (field of view) with 16-slice CT scanning protocol which may be done in some studies for purposes of reassessment of coronary bypass procedure. The mean ED increased from 9.8 ± 4.3 mSv to 14.8 ± 8.5 mSv if the scan range increased from 100 mm to 149 mm with the normal exposure parameter set at 120 kVp.[24,29,36] Thus, the dose increased considerably with an extended scanning coverage area. However, the radiation dose was not compared between genders in 16-slice CT due to insufficient number of studies that had been conducted. One study was performed with 40-slice CT scanner (Brilliance 40 Philips Medical System) in coronary angiography (Table 1). Here the effective radiation dose was reported to be 9.9 ± 2.8 mSv, which is close to the 16-slice CT dose report (10.4 ± 4.9 mSv).[41]

64-slice CT

Twenty-eight studies were carried out using 64-slice CT and a number of comparisons were undertaken between them with different CT models. These are shown in Table 2. The comparisons consist of detector technology (single-source and dual-source CT), scanning protocol (prospective and retrospective ECG-gating), and tube voltage (100 and 120 kVp). Overall ED estimation in 64-slice CT was 10.0 ± 6.2 mSv. With conventional retrospective ECG-gating technique, the mean dose of 64-slice CT was 11.8 ± 5.9 mSv compared to prospectively ECG-gating protocol with estimated ED being 4.1 ± 1.7 mSv. The ED was compared between 100 kVp and 120 kVp scanning protocols from five studies,[31,38,42,45,61] with a total of 724 patients, with the corresponding mean ED at 5.6 ± 3.0 mSv and 10.7 ± 5.1 mSv, respectively, resulting in a dramatic dose reduction of 48 per cent ($p<0.01$).

Eight out of the 28 studies that were performed with 64-slice CT were scanned with dual-source CT scanners, which were all manufactured by Siemens Medical Solutions. In general, the mean ED in both single source CT (SSCT) and dual-source CT (DSCT) scanners was reported as 11.7 ± 6.3 mSv and 6.7 ± 4.6 mSv, respectively (Figure 3). However, the mean ED was differentiated between prospective and retrospective ECG-gating protocols in both scanners with use of DSCT and SSCT. The ED was 9.5 ± 3.9 mSv and 2.8 ± 1.7 mSv in studies performed with retrospective and prospective ECG-gating with DSCT, and 13.4 ± 5.7 mSv and 6.8 ± 5.1 mSv in studies using retrospective and prospective ECG-gating with SSCT, respectively, indicating a significant reduction of ED with prospective gating ($p<0.01$).

The purpose of padding is to provide extra phase information to compensate for variations in heart rate by adding time before and after the centre phase of the acquisition. Padding is described in the range of 0-200 ms and is added to both sides of the centre of the acquisition with padding 0 corresponding to a window of 100 ms scanning time and padding 100 corresponding to a window of 200 ms scanning time.[80] Application of padding helps to generate diagnostic images in patients with high heart rate variations; however, this leads to an increase of ED when compared with those without padding.[55] The effect of different paddings on radiation dose in prospective ECG-gating protocols was conducted in one study,[55] and the results showed that ED was estimated with 5.8 ± 1.8 mSv and 7.4 ± 3.0 mSv with use of 100 ms and 200 ms padding respectively. In contrast, the ED was much lower without padding, [55] which is 3.8 ± 1.2 mSv.

128-, 256- and 320-slice CT

With latest CT models such as 128-, 256- and 320-slice CT, prospective ECG-gating was found to dominate most scanning protocols, as shown in this analysis. Therefore, the mean ED was estimated for each generation of scanner with 3.6 ± 0.4 mSv, 3.0 ± 1.9 mSv and 7.6 ± 1.6 mSv in 128-, 256- and 320-slice CT respectively. However, some studies were conducted using retrospective ECG-gating in these latest CT generations. The mean estimation of ED was reported with 12.4 ± 1.4 mSv, 11.3 ± 3.8 mSv and 13.5 ± 0.7 mSv in 128-, 256- and 320-slice CT respectively. In the 256-slice CT study, the analysis showed that mean ED in retrospective ECG-gating protocol was even lower with use of tube current modulation (10.3 ± 3.7 mSv) than it was without using tube current modulation (14.1 ± 1.9 mSv).[13]

Table 3 shows studies performed with 320-slice CT, where all studies were conducted with prospective ECG-gating protocol. However, only one study used multiple heartbeats scanning protocol for higher heart rates in order to allow more data reconstruction.[72] A study comparing the radiation dose between single and multiple heartbeat [72] showed that the ED increases from 5.7 ± 1.7 mSv to 16.5 ± 4.2 mSv with use of up to three heartbeat scanning.[72] However, in comparison with the latest generation of MDCT scanners, the ED in 320-slice CT with single-heartbeat scan is still higher than that estimated in 128- (3.6 ± 0.4 mSv) and 256-slice CT (3.0 ± 1.9 mSv).

Figure 4 shows the range of mean ED reported in this review based on different CT scanner generations. It is difficult to tell whether or not the increase of CT slices leads to an increase in the radiation dose since various dose saving strategies have been increasingly used in recent generations of MDCT scanners.

Discussion

This review indicates that radiation dose has risen from early generation scanners of 4-slice to 16- and 64-slice CT and will continue to do so if no dose-saving strategies are applied. With increased use of MDCT in coronary imaging due to technological developments the awareness of radiation risk has increased. Thus more and more dose-saving strategies are being employed to reduce the radiation dose while acquiring diagnostic images. This analysis confirms the trend as variable dose-reduction approaches were applied in recent CT scanners, especially 64-slice coronary CTA. This includes the highly effective strategy of ECG-controlled tube current modulation and very effective strategy of prospective ECG-gating, which result in a significant reduction of radiation dose.

Despite promising results of coronary CT angiography, coronary CTA suffers from the disadvantage of high radiation dose, and associated high radiation risks.[1,77] Brenner and Hall[1] estimated that approximately between 1.5 and 2% of all cancers in the United States may be caused by radiation exposure from CT examinations. Davies et al estimated that in the UK radiation from CT scans causes 800 cancers per year in women and 1,300 in men.[78] Radiation exposure is especially unsafe for young and female patients as radiation effects are more severe in these groups than in older individuals and in men. Thus, protecting young and female patients from high radiation doses is very important. A recent study reported that one in 270 women aged 40 years who undergoes coronary CT angiography will develop cancer.[79] Therefore, coronary CT angiography should be performed with dose-saving strategies whenever possible so as to reduce the radiation dose to patients.

Several techniques were introduced to reduce the radiation dose in coronary CT imaging in order to accomplish the rule 'as low as reasonably achievable' (ALARA). Variable dose reduction techniques were applied in the studies, which included ECG-controlled tube current modulation, lower x-ray tube voltage, and prospective ECG-gated scanning.[18] ECG-controlled tube current modulation technique is regarded as one of the highly effective approaches for dose reduction.[80] This approach indicates that tube current can be adjusted in different cardiac phases so that high-quality diagnostic images of coronary arteries during the reconstruction window, and low-quality, higher noise images of the cardiac chamber and cardiac valves during the rest of the cardiac cycle can be achieved. This algorithm restricts the prescribed tube current to a pre-defined time window during the diastolic phase and decreases tube current in the systolic phase of the cardiac cycle, thus achieving significant dose reduction with this method.[26]

With use of tube current modulation in MDCTA, radiation dose can be reduced between 20 to 50% depending on heart rate.[16,38,67,81] This corresponds to our analysis that showed dose reduction between 38 and 51% in 4-, 16-, 64- and 128-slice CT. Another effective approach to reduce radiation dose is to adjust the tube voltage, kVp. Although using a 100-kVp exposure reduces radiation dose between 33 and 48% in 16-slice and 64-slice CT compared to 120 kVp protocols, it should be emphasised that a low tube voltage protocol is only recommended in patients with small body mass index (BMI) [82] or with BMI less than 25 $kg \cdot m^{-2}$in order to keep the image quality at the diagnostic level.

Since the time that 64-slice CT was introduced, prospective gating technique has been increasingly used in coronary CT scanning due to its capability to lower radiation doses notably. This is reflected in our findings as the researchers showed increased concerns about the radiation dose associated with coronary CTA in application of variable dose-saving strategies. Prospective ECG-gating method is reported to reduce the ED between 70 and 87% compared to retrospective ECG gating, and results from this review are consistent with other reports.[59,83,84] According to this analysis, radiation dose was reduced between 66 and 73% with regard to any slice CT generations.

Further dose reduction can be achieved by a combination of prospective ECG gating with high pitch spiral acquisition, which results in a consistent dose below 1 mSv.[63,69] This is only achievable with the second generation of dual-source CT scanners with acquisition of 128-slices per gantry rotation, and high temporal resolution of 75 ms.[69] There is no doubt that prospective gating represents the very effective approach in reducing radiation dose; however, its application is limited to patients with a regular and low heart rate (<65 bpm), and no functional information is available from the scan.

Studies performed with 4-slice and 16-slice CT have shown that the effective radiation dose was estimated in female significantly higher than in male patients due to the different size thickness on the chest region. However, the breast tissue is radiosensitive and keeping the radiation dose to the breast at the minimum level is paramount. This also highlights the importance of reducing radiation dose in young female patients. It is estimated that ED of coronary CTA may reach up to 40 mSv in female patients if no dose-saving strategies are applied and there is associated radiation exposure to breast tissues.[84]

There are some limitations in this analysis. First, the searching criteria included only citations on radiation dose in coronary CT angiography from the selected databases. Five per cent of the articles were in non-English languages and were thus excluded from this review. Second, although there were many references especially on earlier types of CT scanners, the reports were limited to diagnostic accuracy, as most of the publications focused on image quality rather than on radiation dose. The development of CT scanners in particular, enabled researchers to improve the scanning technique or diagnostic quality but did nothing to raise awareness of radiation risk. Third, this analysis only looked at the radiation dose and did not assess diagnostic value or image quality related to different types of CT scanners. However, literature on the diagnostic accuracy of MDCT in CAD has been extensively studied and a number of meta-analyses have been published to show the increased accuracy of MDCT from 4-slice to

64-slice CT.[85-87] Moreover, most of the studies on 256- and 320-slice CT were based on phantom experiments, which were excluded from the current analysis. Finally, some studies, especially those using 16-slice CT scanners did not provide detailed information about radiation dose in relation to gender. Thus, it is difficult to perform a comparison with other types of MDCT scanners.

Conclusion

Diagnostic value of MDCT angiography in the diagnosis of coronary artery disease has improved significantly with technological developments of MDCT technique, leading to increased application of MDCT in cardiac imaging. The amount of radiation dose that is associated with cardiac MDCT remains a major point of deliberation in clinical practice and is reflected in the increased use of dose-saving strategies, as shown in this analysis. With the latest MDCT scanners achieving high diagnostic accuracy, reduction of radiation dose has become a major concern to clinicians and manufacturers. Furthermore, awareness amongst clinicians to reduce radiation doses because of the risks associated with radiation has increased. This is indicated in the fact that more and more dose-saving strategies are being implemented in coronary CT angiography examinations.

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Figure legends

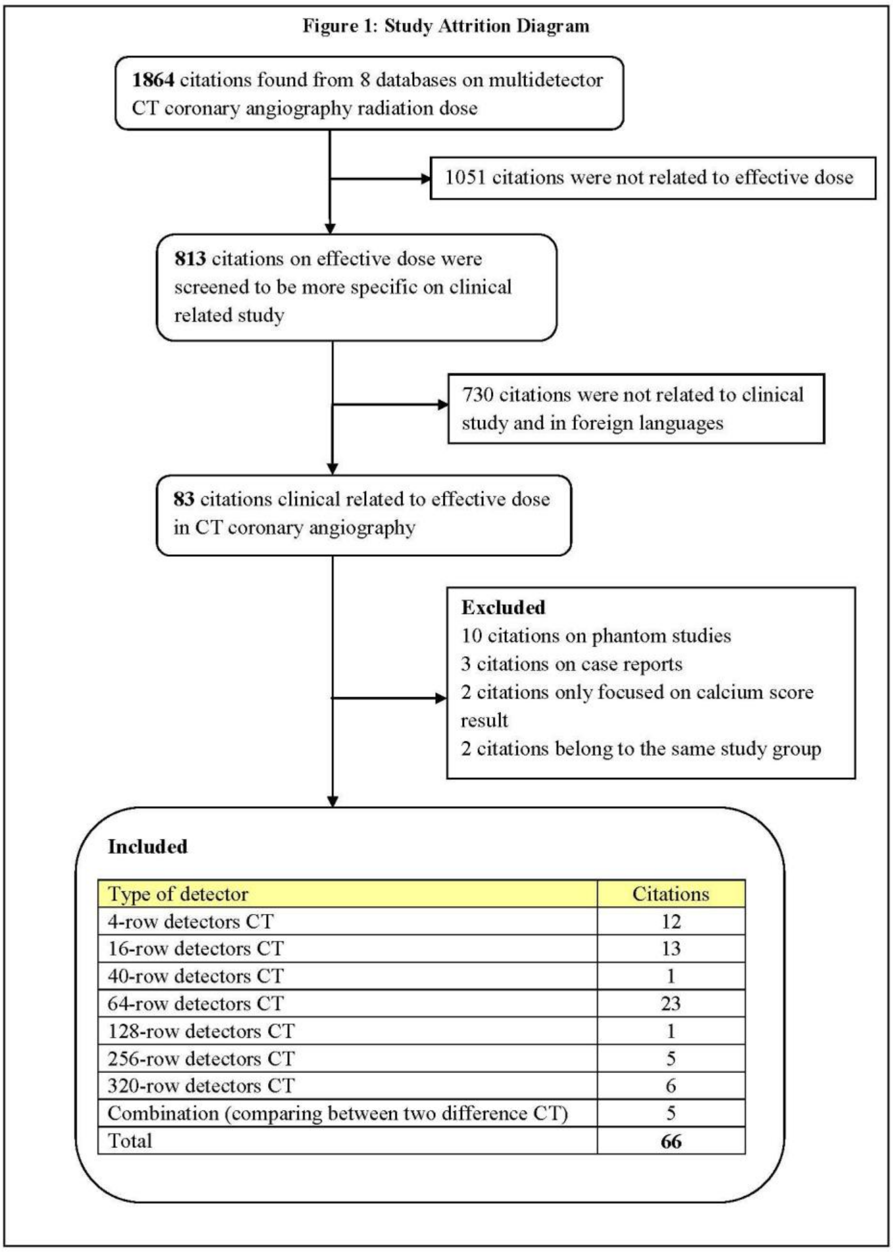
Figure 1. Flow chart showing the search strategy of eligible references.

Figure 2. Different manufacturers are used in different multidetector CT scanners.

Figure 3. Box plot shows the mean effective dose reported in the studies with use of retrospective ECG-gating and prospective ECG-gating. It is obvious that the radiation dose of prospective gating MDCT angiography was significantly lower than that of retrospective gating protocol. Horizontal line in each box shows median and top and bottom lines of boxes show interquartile range (IQR). Whiskers show lowest value still within 1.5 IQR of lower or upper quartile, however, highest value for retrospective ECG-gating is outside 1.5 IQR of upper quartile.

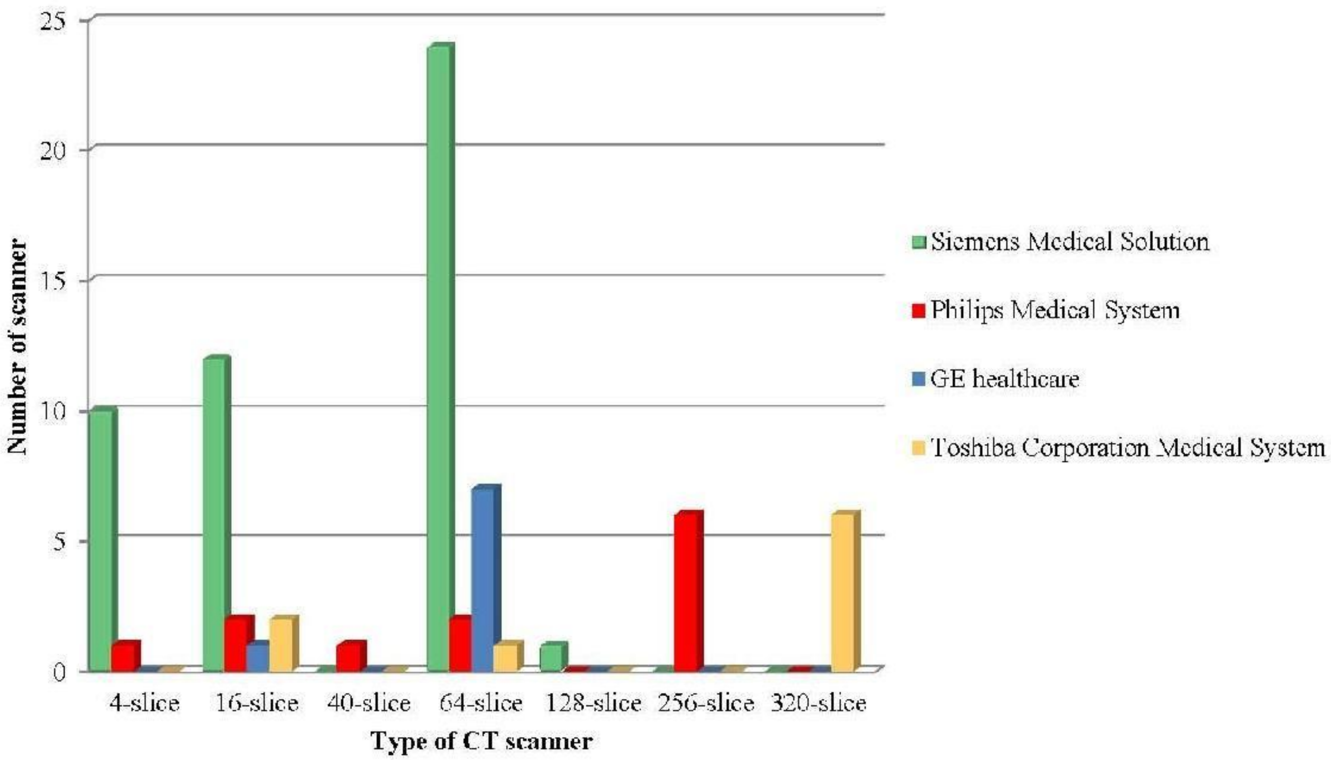
Figure 4. Distribution of mean effective dose between 4-, 16-, 64-, 128-, 256- and 320-slice multidetector CT scanners is displayed the box plot. Radiation dose increases with the increase of number of slices; in particular, this is apparent when comparing 4-slice with 16- and 64-slice CT. With latest models such as 128-, 256- and 320-slice CT, radiation dose was reduced to some extent as prospective gating is commonly used. Horizontal line in each box shows median and top and bottom lines of boxes show interquartile range (IQR). Whiskers show lowest value still within 1.5 IQR of lower or upper quartile, however, the highest value for 16-sliec CT studies is outside 1.5 IQR of upper quartile.

Fig. 1



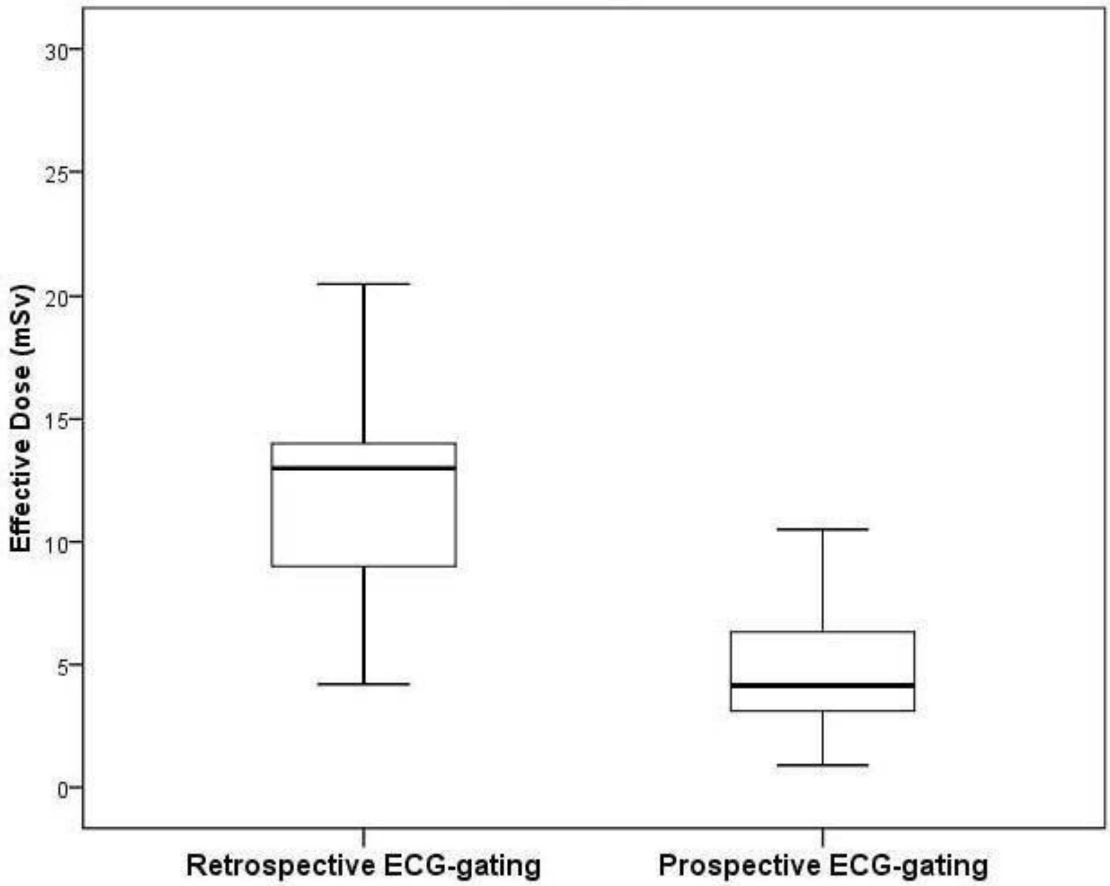
Type of detector	Citations
4-row detectors CT	12
16-row detectors CT	13
40-row detectors CT	1
64-row detectors CT	23
128-row detectors CT	1
256-row detectors CT	5
320-row detectors CT	6
Combination (comparing between two difference CT)	5
Total	**66**

Fig. 2



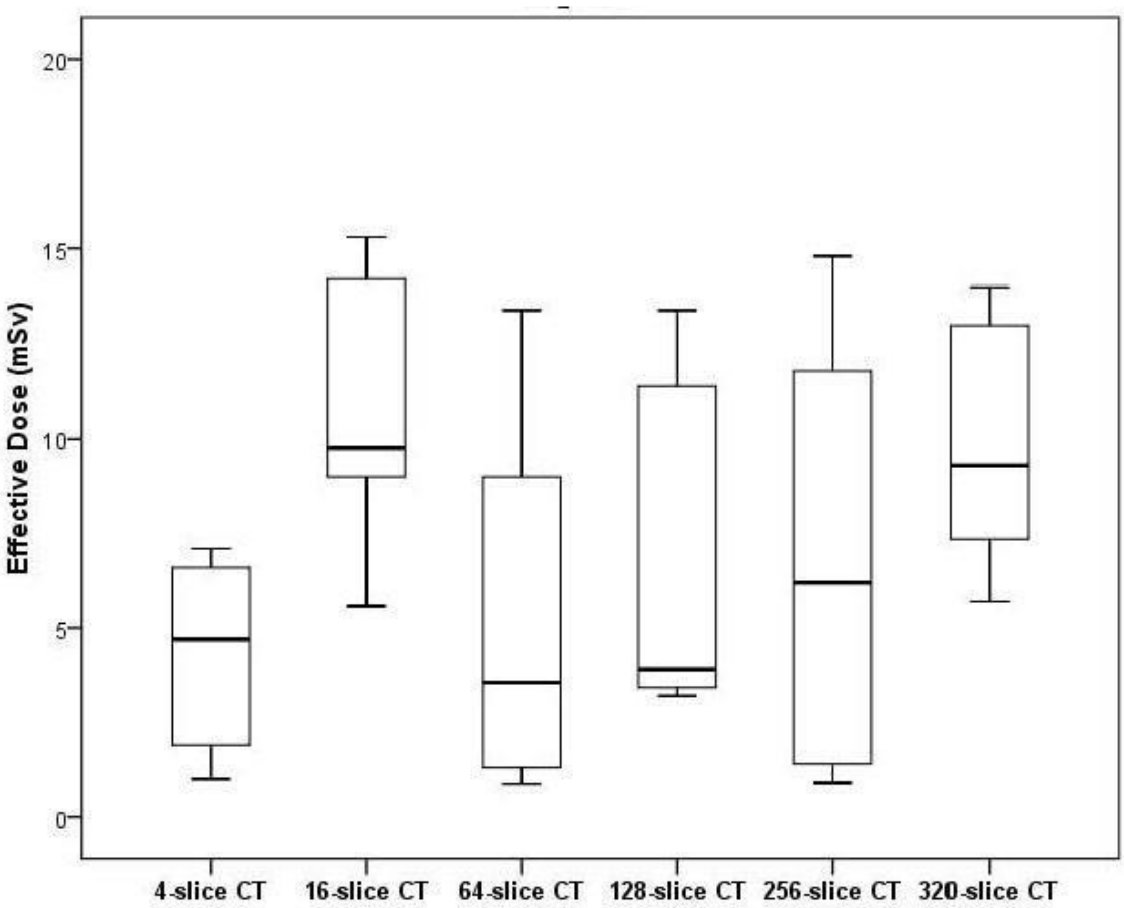
0
5
10
15
20
25
Number of scanner
4-slice
16-slice
40-slice
64-slice
128-slice
256-slice
320-slice
Type of CT scanner
Siemens Medical Solution
Philips Medical System
GE healthcare
Toshiba Corporation Medical System

Fig. 3



0
5
10
15
20
25
30
Effective Dose (mSv)
Retrospective ECG-gating
Prospective ECG-gating

Fig. 4



Effective Dose (mSv)
20
15
10
5
0
4-slice CT
16-slice CT
64-slice CT
128-slice CT
256-slice CT
320-slice CT

Table 1: Study details of 4-slice, 16-slice and 40-slice CT coronary angiography

Author/Year of publication	No. of Patients (male/female)	Mean Age (years)	Effective dose (mSv) (male/female)	Scanning method/Dose saving strategy	Detector collimation (mm)	GRT (ms)	Pitch	Tube voltage (kVp)	Tube current (mA)
Achenbach et al.[13]/ 2000	16/9	56	3.9/5.8	Retrospective	4 × 1.0	500	0.375	140	150
Becker et al.[14]/ 2002	27/1	64	7.1/9.6	Retrospective	4 × 1.0	500	NS	120	300
Haberl et al.[15]/ 2005	83/50	67	5.8-7.4/ 7.6-9.8	Retrospective	4 × 1.0	NS	NS	120	300
Jakobs et al.[16]/ 2002	36/14	56.3	1.0/1.4	Retrospective/ TCM/High pitch	4 × 2.5	500	1.5	120	100*
	36/14	55.7	1.9/2.5	Retrospective/ High pitch	4 × 2.5	500	1.5	120	100*
Knez et al.[20]/ 2001	38/6	60	9.5	Retrospective	4 × 1.0	500	NS	NS	-
Kopp et al.[17]/ 2002	79/27	62	5.5/6.5	Retrospective/ High pitch	4 × 1.0	500	1.5-2.0	120	300
Leber et al.[19]/ 2003	72/19	61.7	8.2	Retrospective	4 × 1.0	NS	NS	120	300
Mahnken et al.[22]/ 2003	27/8	62.3	5.4/7.8	Retrospective	4 × 1.0	500	0.375	120	400*
Nieman et al.[18]/ 2001	27/8	59	4.9	Retrospective/ High pitch	4 × 1.0	500	1.5-2.0	140	-
Roos et al.[21]/ 2002	20	60	8.85	Retrospective	4 × 1.0	500	0.38-0.75	120	250-400
	20	60	3.65	Prospective	4 × 2.5	500	1.0	140	150
Schroeder et al.[23]/ 2003	13/2	58	6.7-10.9/ 8.1-13	Retrospective	4 × 1.0	500	1.5	140	400*
Anders et al.[24]/ 2006	29/3	67	3.4-4.8/ 5.1-7.1	Retrospective/ TCM	12 × 0.75	420	NS	120	500*
Chiou et al.[25]/ 2005	65/7	58	9.0	Retrospective	12/16 × 0.75	420	NS	120	500
Coles et al.[26]/ 2006	27/13	60	15.3	Retrospective	16 × 0.75	420	NS	120	550*
	31/20	64	14.2	Retrospective	12 × 0.75	420	NS	120	500*
Deetjen et al.[37]/ 2007	39/17	65.96	9.76	Retrospective/ TCM	16 × 0.75	375	NS	120	550*
	41/10	58.84	5.58	Retrospective/ TCM/AEC	16 × 0.75	375	NS	120	550*
Dill et al.[27]/ 2008	49/7	66	9.76	Retrospective	16 × 0.75	375	0.16-0.2	120	550*

Garcia et al.[28]/ 2006	162/76	59.8	8.0	Retrospective/ TCM	16 × 0.75	NS	NS	120-140	400-500
Hausleiter et al.[38]/ 2006	27/33	59.1	10.6	Retrospective	16 × 0.75	420	0.18	120	510
	33/33		6.4	Retrospective/ TCM	16 × 0.75	420	0.18	120	304
	34/34		5	Retrospective/ Low kV	16 × 0.75	420	0.21	100	387
Houslay et al.[29]/ 2007	43/7	66	18.5	Retrospective	16 × 1.00	500	0.25	135	250-300
Hoffmann et al.[30]/ 2005	57	61.5	8.1	Retrospective	16 × 0.75	420	0.2	120	240
	46		4.9	Prospective/TCM	16 × 0.75	420	-	140	300
Kuettner et al.[31]/ 2004	44/16	58.3	5.4	Retrospective/ TCM	12 × 0.75	NS	NS	120	500
			10.1	Retrospective	12 × 0.75	NS	NS	120	500
Leta et al.[32]/ 2004	28/3	66	24.2	Retrospective	NS	NS	NS	120	250-350
Mollet et al.[33]/ 2004	113/15	58.9	9.85	Retrospective	16 × 0.75	420	NS	120	400-450
Nieman et al.[34]/ 2002	34	58	8-9	Retrospective	12 × 0.75	420	NS	120	400-450
Park et al.[35]/ 2009	105	55.9	7.8	Retrospective/ Low kVp	16 × 0.75	420	0.2	100	600-630
	80	56.5	10.1	Retrospective	16 × 0.75	420	0.2	120	550-600
Rixe et al.[39]/ 2009	49/7	68	9.8	Retrospective	16 × 0.75	NS	0.2-0.24	120	550
Van-Mieghem et al.[40] /2006	27	61.2	11.8-16.3	Retrospective	16 × 0.75	420	NS	120	400-450
Yamamoto et al.[36]/ 2006	36/6	63.6	20.8	Retrospective	16 × 0.625	500/6	0.275	NS	350
Gaspar et al.[41]/ 2005	20/20	63.1	9.9	Retrospective	40 × 0.625	420	0.2	120	600-800

TCM= ECG-controlled tube current modulation; GRT= Gantry rotation time;*=effective mAs; NS= Not stated

Table 2: Study details of 64-slice CT coronary angiography

Author/ Year of publication	No. of patients (male/ female)	Mean Age (years)	Effective Dose (mSv)	Scanning method/Dose saving strategy	No. of detector collimation (mm)	GRT (ms)	Pitch	Tube voltage (kVp)	Tube current (mA)
Alkadhi et al.[42]/ 2008	36/14	57	9.0	Retrospective	2 × 32 × 0.6	330	0.2-0.5	120	330*
	15/13	61.5	2.9	Prospective/ TCM#	2 × 32 × 0.6	330	NS	120	330 *
	28/15	59.9	4.2	Retrospective / Low kVp	2 × 32 × 0.6	330	0.2-0.5	100	220*
	26/14	62.9	1.3	Low kVp/ Pro/ TCM#	2 × 32 × 0.6	330	NS	100	190*
Achenbach et al.[63]/ 2010	50	NS	0.87	Prospective/High pitch	2 × 64 × 0.6	280	3.2-3.4	100	220-290
Blankstein et al.[43]/ 2009	114/74	56.5	13.4	Retrospective	2 × 32 × 0.6	330	0.3	80-140	320
	26/16	44.3	3.2	Prospective	2 × 32 × 0.6	330	-	80-140	200
Deetjen et al.[37]/ 2007	25/22	57.36	13.58	Retrospective / AEC	64 × 0.6	330	NS	120	850
Earls et al.[44]/ 2008	44/38	55.6	18.4	Retrospective /TCM	64 × 0.625	350	NS	120	647
	71/50	56.7	2.8	Prospective/ Padding (0-100ms)	64 × 0.625	350	NS	120	508
Feuchtner et al.[45]/ 2009	26	53.1	9.6	Retrospective Low kVp	32 × 0.6	330	0.2	100	500-800
	26		5.3	Retrospective Low kVp/TCM	32 × 0.6	330	0.2	100	500-800
	25	55.3	18.2	Retrospective	32 × 0.6	330	0.2	120	600-900
	26		8.7	Retrospective / TCM	32 × 0.6	330	0.2	120	600-900
Francone et al.[46]/ 2007	108/6	63.1	9.5	Retrospective/CARE Dose 4D	32 × 2 × 0.6	330	0.2	120	800
Freeman et al.[47]/ 2009	157	56	20.3	Retrospective	64 × 0.625	350	NS	NS	NS
	748		3.02	Prospective/single	64 × 0.625	350	NS	NS	NS
	359		6.96	Prospective/multiphase	64 × 0.625	350	NS	NS	NS
Hausleiter et al.[38]/ 2006	34/34	59.3	14.8	Retrospective	64 × 0.6	330	0.2	120	870
	36/36		9.4	Retrospective /TCM	64 × 0.6	330	0.2	120	551
	21/49		5.4	Retrospective/ Low kVp/TCM	64 × 0.6	330	0.2	100	537
Hausleiter et al.[48]/ 2009	384	NS	19	Prospective/ Retrospective /±AEC/±TCM	64 × 0.625	NS	NS	100-120	NS
	123	NS	10	Prospective/ Retrospective/	64 × 0.625	NS	NS	120	NS

				±AEC/±TCM					
	380	NS	9	Retrospective/ ±AEC/±TCM	64 × 0.6	NS	NS	120	NS
	521	NS	11	Retrospective /±AEC/±TCM	2 × 32 × 0.6	NS	NS	100-120	NS
	138	NS	15	Retrospective /±AEC/±TCM	NS	NS	NS	120	NS
Husmann et al.[49]/ 2010	28/12	54.9	2.1	Retrospective /± Low kVp	64 × 0.625	350	NS	100-120	400-650
Klass et al.[64]/ 2009	58/22	58	3.36	Prospective	64 × 0.625	420	NS	120-140	150-210
Leber et al.[50]/ 2005	59	NS	10-14	Retrospective	64 × 0.6	330	NS	120	550-750
Maruyama et al.[51]/ 2008	71/26	69.9	21.1	Retrospective / TCM	64 × 0.625	350	NS	120	800
	47/29	69.1	4.3	Prospective	64 × 0.625	350	NS	120	800
Meijboom et al.[52]/ 2007	279/123	60	13.4-17.0	Retrospective	32 × 2 × 0.6	330	NS	120	850-960
Mollet et al.[53]/ 2005	34/18	59.6	15.2-21.4	Retrospective	32 × 2 × 0.6	330	NS	120	900
Nikolaou et al.[54]/ 2006	59/13	64	8-10	Retrospective/ TCM	32 × 2 × 0.6	330	NS	120	850
Pontone et al.[55]/ 2009	65/15	64.3	20.5	Retrospective	64 × 0.625	350	NS	120	700
	70/10	64.8	5.7	Prospective/ Padding 100-400ms	64 × 0.625	350	NS	120	700
Pugliese et al.[56]/ 2006	35	61	15-20	Retrospective	32 × 2 × 0.6	330	NS	120	900
Raff et al.[57]/ 2005	53/17	59	13-18	Retrospective	32 × 0.6	330	NS	120	750-850
Rixe et al.[39]/ 2009	22/33	55	8.6	Retrospective	64 × 0.6	330	0.2-0.24	120	850
	95	60	9.6	Retrospective	64 × 0.6	330	0.2-0.5	120	320
	25	60	3.8	Retrospective / Low kVp	64 × 0.6	330	0.2-0.5	100	320
Ropers et al.[58]/ 2006	52/32	58	7.5-11.2	Retrospective	64 × 0.6	330	NS	120	750
Shuman et al.[59]/ 2008	31/19	47.5	26.7	Retrospective/ TCM	64 × 0.625	330	0.2-0.24	120	600-790
	33/17	46	6.2	Prospective	64 × 0.625	330	1.0	100-120	400-500
Stolzmann et al.[5]/ 2010	70/30	64.5	8.1	Retrospective	2 × 32 × 0.6	330	0.2-0.38	100-120	330
	58/42	68	2.2	Prospective	2 × 32 × 0.6	330	0.2-0.38	100-120	190
Van Mieghem et al.[40]/ 2006	43	61.2	15.2-21.4	Retrospective	64 × 0.6	330	NS	120	900
Wang et al.[60]/ 2009	68/32	53.1	5.9-9.1	Retrospective	2 × 32 × 0.6	NS	0.2-0.43	120	320
	42/18	52.5	9.3	Retrospective	64 × 0.6	NS	0.2	120	770
Xu et al.[61]/ 2009	26/24	54.6	7.4	Retrospective / TCM/ Low kVp	2 × 32 × 0.6	330	0.31-0.44	100	362

	25/25	54.6	3.4	Prospective/Low kVp	2 × 32 × 0.6	330	NS	100	418
	26/24	56.2	15.5	Retrospective / TCM	2 × 32 × 0.6	330	0.31-0.44	120	410
	25/25	56.2	6.5	Prospective	2 × 32 × 0.6	330	NS	120	506
Zhao et al.[62]/ 2009	25/5	58.7	14.6	Retrospective	2 × 32 × 0.6	330	NS	100-120	330-430
	23/7	58.7	2.2	Prospective	2 × 32 × 0.6	330	NS	100-120	200-260

TCM= ECG-controlled tube current modulation; *=effective mAs; #= Attenuation based tube current modulation; NS= Not stated;

Table3: Study details of 128-slice, 256-slice and 320-slice CT coronary angiography

Author/ Year of publication	No. of patients (male/female)	Mean Age	Effective Dose (mSv)	Scanning method/Dose saving strategy	No.of detector collimation (mm)	GRT (ms)	Pitch	Tube voltage (kVp)	Tube current (mA)
Alkadhi et al.[69]/ 2010	38/12	62	1.4	Prospective	2 × 64 × 0.6	280	0.2-0.5	100	320
	36/14	63	0.9	Prospective/ High pitch	2 × 64 × 0.6	280	3.4	100	320
Chao et al.[65]/ 2010	80/24	61.5	14.8	Retrospective	256 × 0.625	270	NS	120	592
	80/24	61.5	5.1	Prospective	256 × 0.625	370	NS	120	925
Chen et al.[66]/ 2010	5/5	56.3	7.3	Retrospective	256 × 0.625	270	NS	120	700-900
	3/7	57.9	11.8	Retrospective/ TCM	256 × 0.625	270	NS		
	8/2	60	4.7	Prospective/ Padding window	256 × 0.625	270	NS		
	5/5	54.8	2.7	Prospective	256 × 0.625	270	NS		
Efstathopoulos et al.[70]/ 2009	5/5	55.2	3.2	Prospective	128 × 0.625	270	NS	120	180-250
	12/3	55.2	13.4	Retrospective	128 × 0.625	270			800-950
Klass et al.[64]/ 2009	58/22	60	3.42	Prospective	2 ×128 ×0.625	270	NS	120-140	150-250
Walker et al.[67]/ 2009	2,811	NS	3.8	Prospective	2 ×128 ×0.625	270	0.18	120	800
Weigold [68]/ 2009	77/12	NS	11.4	Retrospective	128 × 0.625	270	NS	120	NS
	77/12	NS	4.0	Prospective	128 × 0.625	270	NS	120	NS
Dewey et al.[71]/ 2009	21/9	61	8.1	Prospective	320 × 0.5	350	NS	120	350-450
Hein et al.[3]/ 2009	19/11	63.2	10.5	Prospective	320 × 0.5	350	NS	120	400
Hoe and Toh [72]/ 2009	109/42	56.3	5.7	Prospective/ 1-HB	320 × 0.5	350	NS	100-120	300-580
	24/12	54.7	13.0	Prospective/ 2-HB	320 × 0.5	350	NS	120	
	9/3	55.7	17.5	Prospective/ 3-HB	320 × 0.5	350	NS	120	
Graaf et al.[73]/ 2010	34/30	61	3.9-10.8	Prospective	320 × 0.5	350	NS	100,120,135	400-580
Rybicki et al.[4]/ 2008	5/1	61.5	14	Retrospective	320 × 0.5	350	NS	120	400-580

	23/11	52.7	7.2	Prospective	320 × 0.5	350	NS	120	
Steigner et al.[74]/ 2009	28/13	53	6.7	Prospective	320 × 0.5	350	NS	120	400-580

TCM=ECG-controlled tube current modulation GRT= Gantry rotation time; HB= Heart beat; NS= Not stated