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Coronary CT angiography with single-source and dual-source CT: Comparison of image quality and radiation dose between prospective ECG-triggered and retrospective ECG-gated protocols

Authors:

Akmal Sabarudin MSc^{1,2}, Zhonghua Sun PhD¹, Ahmad Khairuddin Md Yusof MMed³

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

² Diagnostic Imaging & Radiotherapy Programme, Faculty of Health Sciences, Universiti Kebangsaan Malaysia, 50300 Kuala Lumpur, Malaysia

³ Department of Cardiology, National Heart Institute, 50300 Kuala Lumpur, Malaysia

Corresponding author:

Associate Professor Zhonghua Sun,

Discipline of Medical Imaging, Department of Imaging and Applied Physics, Curtin University, GPO Box, U1987, Perth, Western Australia, 6845, Australia.

Tel: +61-8-9266 7509

Fax: +61-8-9266 2377

Email: z.sun@curtin.edu.au

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Abstract

Background: This study is conducted to investigate and compare image quality and radiation dose between prospective ECG-triggered and retrospective ECG-gated coronary CT angiography (CCTA) with use of single-source CT (SSCT) and dual-source CT (DSCT).

Methods: A total of 209 patients who underwent CCTA with suspected coronary artery disease scanned with SSCT ($n=95$) and DSCT ($n=114$) scanners using prospective ECG-triggered and retrospective ECG-gated protocols were recruited from two institutions. The image was assessed by two experienced observers, while quantitative assessment was performed by measuring the image noise, the signal-to-noise ratio (SNR) and the contrast-to-noise ratio (CNR). Effective dose was calculated using the latest published conversion coefficient factor.

Results: A total of 2,087 out of 2,880 coronary artery segments were assessable, with 98.0% classified as of sufficient and 2.0% as of insufficient image quality for clinical diagnosis. There was no significant difference in overall image quality between prospective ECG-triggered and retrospective gated protocols, whether it was performed with DSCT or SSCT scanners. Prospective ECG-triggered protocol was compared in terms of radiation dose calculation between DSCT (6.5 ± 2.9 mSv) and SSCT (6.2 ± 1.0 mSv) scanners and no significant difference was noted ($p=0.99$). However, the effective dose was significantly lower with DSCT (18.2 ± 8.3 mSv) than with SSCT (28.3 ± 7.0 mSv) in the retrospective gated protocol.

Conclusions: Prospective ECG-triggered CCTA reduces radiation dose significantly compared to retrospective ECG-gated CCTA, while maintaining good image quality.

Introduction

Coronary CT angiography (CCTA) has gained a leading role in the diagnosis of coronary artery disease (CAD) due to its high diagnostic value, in particular, a very high negative predictive value (95–99%) [1,2]. With 64- or more slice CT, non-invasive CCTA has become a reliable alternative to invasive coronary angiography in the diagnosis of patients with suspected CAD [2].

Traditionally, CCTA was performed using retrospective ECG gating, which enables acquisition of volume data, but at the expense of high radiation dose, since data is acquired during a spiral CT protocol [3]. High radiation dose associated with retrospective ECG-gated CCTA raised major concerns in the literature; thus, strategies for reducing radiation dose in retrospective ECG gating have been developed and widely introduced in present-day clinical centres. These strategies include tube current modulation that is either attenuation-based [4,5] or ECG-control-based [6,7], lower tube voltage [8,9], high-pitch scanning [10,11], and prospective ECG triggering [3,12,13]. Of these strategies, prospective ECG triggering represents the most effective approach with a significant dose reduction when compared to the conventional retrospective ECG-gated protocol, but with high diagnostic image quality.

Unlike the principle of retrospective ECG gating, the principle of prospective ECG triggering is that data acquisition takes place only in the selected cardiac phase by selectively turning on the X-ray tube when triggered by the ECG signal, and turning it off or dramatically lowering it during the rest of the R–R cycle [3].

Radiation dose and image quality with prospective ECG triggering are increasingly being studied and compared with retrospective ECG gating in the literature [14-17]. Despite the promising results that have been achieved in dose reduction and image quality, there is a

concern about the accuracy of effective dose calculation. Moreover, to our knowledge there is a lack of systematic investigation on image quality comparison between different types of scanners (single-source vs. dual-source CT) with prospective and retrospective ECG-gated CCTA techniques. Therefore, the aim of this study was to investigate and compare image quality and radiation dose between prospective ECG-triggered and retrospective ECG-gated CCTA protocols, using different types of 64-slice CT scanners.

Materials and methods

Study population

This is a cross-sectional study comparing radiation dose and image quality between prospective triggered and retrospective ECG-gated CCTA in two major public hospitals, Royal Perth Hospital, Perth, Australia, and National Heart Institute, Kuala Lumpur, Malaysia. The study was approved by both the institutional ethical review boards. The first part of the study was conducted retrospectively between January and July 2011 in the Royal Perth Hospital with 95 patients with suspected CAD who underwent CCTA with single-source CT (SSCT). The second part of the study was conducted prospectively with 114 consecutive patients who underwent CCTA between August 2011 and January 2012 with dual-source CT (DSCT) in the National Heart Institute. Written informed consent was obtained from all patients. The data including demographic information (i.e. age, gender, body mass index and heart rate) and scan parameters (i.e. scan duration, longitudinal scan range, tube voltage and pitch) were collected from each patient. Heart rate which was defined as the average heart rate during image acquisition was also recorded for each patient. All patients had sinus heart rhythm. Patients with renal insufficiency presenting with elevated serum creatinine levels (> 1.5 mg/dL), documented hypersensitivity to iodinated contrast materials and any indications related to heart surgery, that is, post-coronary artery bypass graft assessments, heart valve and

pacemaker placement and patients with obvious coronary wall calcifications (calcium score >1000) were excluded from the study.

SSCT scanning protocols

The CCTA protocol was divided into prospective triggering ($n=43$) and retrospective ECG gating ($n=52$), both of which were performed with a 64-slice scanner (Brilliance 64, Philips Healthcare, USA). The CCTA was performed with detector collimation of 64×0.625 mm, slice thicknesses of 0.8 mm, field of view ranging from 150 to 170 mm and adjustable tube current in the range of 300–500 mA with a tube voltage of 120 kV. A pitch of 0.2 and an ECG-pulsing window of 30–80% of the R–R interval were used in retrospective ECG-gated protocol.

DSCT scanning protocols

The CCTA protocol was divided into prospective triggering ($n=50$) and retrospective ECG gating ($n=64$), both of which were performed with a 64-slice CT scanner (Somatom Definition, Siemens Medical Solutions, Germany). CCTA protocol was performed with beam collimation of $2 \times 32 \times 0.6$ mm, slice acquisition of $2 \times 64 \times 0.6$ mm with z-flying focal spot and 320 mAs per rotation and tube voltage of 120 kV. For retrospective ECG-gated protocol, the ECG-pulsing window was set at 30–80% of the R–R interval with pitch of 0.2–0.43, which was automatically adapted to the heart rate.

Contrast medium administration

A minimum of 65 mL contrast agent (*Iomeron* 350 mgI/mL) was administered intravenously at a flow rate of 5.0–5.5 mL/s followed by 50 mL saline flush at 5 mL/s. The amount of contrast medium required for coronary CT examination was calculated according to the following formula: $V = IR \cdot ST$, where V is volume in millilitres, IR is the injection rate (mL/s)

and ST is the scanning time in seconds [18]. Bolus was tracked by using an automated bolus triggering technique at the region of interest, that is, at the ascending aorta, with a baseline threshold of 120 HU (Hounsfield units).

Details about the use of beta-blockers are presented in Figure 1. However, in retrospective ECG-gated protocol, beta-blockers were given only to patients with heart rate > 70 bpm (beats per minute) in the SSCT group and > 100 bpm in the DSCT group.

Analysis of image quality

Assessment of image quality was determined by two experienced viewers with at least 5 years of experience in cardiac CT imaging who were blinded to the acquisition parameters and protocols. Each image was scored subjectively with a 4-point grading scale. Details of the grading scale are presented in Table 1. Each coronary segment was evaluated according to the 16-segment model based on the American Heart Association's (AHA) guidelines [19, 20]. The right coronary artery (RCA) included segments 1-4, the left main coronary artery and left anterior descending coronary artery (LAD) included segments 5-10, and the left circumflex coronary artery (LCx) included segments 11-15. If present, the intermediate artery was designated as segment 16. Coronary artery analysis was performed in all vessels with at least a 1.0-mm luminal diameter at their origin. If the segment was not present due to anatomical variants, image quality was recorded as missing. Sufficient quality (score 1, 2 and 3) was defined as excellent, good and moderate, respectively, which was considered to be evaluable for diagnosis. Insufficient image quality was ranked with a score of 4 which was described as poor or of no diagnostic value.

The image quality was also measured quantitatively with a commercially available software Analyze 7.0 (Analyze, version 7.0 for Windows, Kansas, USA). The objective parameters of

image quality included CT attenuation, image noise, signal-to-noise ratio (SNR) and contrast-to-noise ratio (CNR). CT attenuation was measured in HU and defined as the mean value while image noise was measured in terms of standard deviation (SD). Both CT attenuation and image noise were measured at three different regions of interest (ROI) with a circular ROI of 200, 7, and 3–5 mm² placed at the ascending aorta, perivascular fatty tissue and coronary artery (left main and proximal right coronary artery), respectively (Figure 2). The SNR was determined by dividing CT attenuation with image noise, while CNR was calculated by dividing contrast enhancement (CT attenuation at the aorta minus CT attenuation at the fat) with image noise, that is, $CNR_{aorta} = \frac{Mean_{aorta} - Mean_{fat}}{SD_{aorta}}$ [21].

Estimation of effective dose

The effective dose (E) was estimated by multiplying the dose-length product (DLP) with a conversion coefficient factor (E/DLP), k (mSv·mGy⁻¹·cm⁻¹). The DLP value is available on the scanner console and the k factor of 0.026 mSv·mGy⁻¹·cm⁻¹ was used for the cardiac region instead of chest CT (0.014 or 0.017 mSv·mGy⁻¹·cm⁻¹) based on International Commission on Radiological Protection (ICRP-103) publication [22, 23]. Since the conversion coefficient factor of 0.017 mSv·mGy⁻¹·cm⁻¹ is widely used in the literature [24], the results of effective dose were also provided by using a conversion coefficient factor of 0.017 mSv·mGy⁻¹·cm⁻¹ for comparison.

Statistical analysis

All data were entered into SPSS V17.0 (SPSS, version 17.0 for Windows, Chicago, Illinois, USA) for statistical analysis. A p value of <0.05 was considered to indicate a statistically significant difference. The values were normally distributed in all prospective and retrospective ECG-gated groups with inclusion of DSCT and SSCT. Those values were

compared with one-way analysis of variance (ANOVA) for multi-factor interaction analysis. The doses from each protocol were presented in box plots while the correlation between E and body mass index (BMI) was analysed with Pearson's correlation in both prospective **triggered** and retrospective ECG-**gated** groups between DSCT and SSCT. For image quality parameter, inter-observer agreement for image analysis was estimated by kappa statistics and classified as follows: poor ($\kappa < 0.20$); fair ($\kappa = 0.21-0.40$); moderate ($\kappa = 0.41-0.60$); good ($\kappa = 0.61-0.80$) and excellent agreement ($\kappa = 0.81-1.00$). Kruskal-Wallis test was conducted for further statistical non-parametric analysis in image quality assessment. Quantitative image analysis such as CT attenuation, image noise, SNR and CNR were compared using the Student's t -test.

Results

Details on patient demographics, CAD risk factor and beta-blocker usage are presented in Table 2. A total of 2,880 coronary artery segments were evaluated. However, 793 segments (mainly posterior lateral branch, second diagonal artery, second obtuse marginal branch and ramus intermedius segment) were not considered because of anatomical variants. Therefore, 2,087 segments were assessable of which 2,046 (98.0%) segments were ranked as of sufficient image quality (score 1 to 3), while only 41 segments (2.0%) were classified as of insufficient image quality (score 4) regardless of prospective or retrospective ECG-**gated** CCTA protocols.

Diagnostic performance of image quality

The image quality of coronary artery segments was assessed by two readers with a kappa score of 0.65 and 0.62 for both prospective and retrospective ECG-**gated** group respectively, indicating good inter-observer agreement. In the retrospective ECG-**gated** group, evaluation

was undertaken with reconstructions at the mid-diastolic phase in 70% of the patients (81/116), resulting in better image quality, while for the remaining 30% of patients, reconstruction was selected at the end-systolic phase.

Image quality was rated as excellent (image quality score 1) in 182/528 (34.5%) and 120/504 (23.8%) for the retrospective ECG-gated group, 152/504 (30.2%) and 244/551 (44.3%) for the prospective ECG-triggered group with DSCT and SSCT, respectively. Moreover, sufficient image quality with scores of 2 and 3 was found in 342/528 (64.8%) and 375/504 (74.4%) coronary segments with protocols using retrospective ECG-gated DSCT and SSCT groups, whereas this was found in 343/504 (68.0%) and 288/551 (52.3%) coronary segments in the prospective ECG-triggered DSCT and SSCT groups. Insufficient image quality (score 4) was found in 4/528 (0.8%) and 9/504 (1.8%) coronary segments for the retrospective gated group and in 9/504 (1.8%) and 19/551 (3.4%) coronary segments for the prospective triggered group, corresponding to DSCT and SSCT, respectively. Although DSCT led to fewer instances of insufficient image quality, there were no significant differences in the mean quality scores between prospective triggered and retrospective ECG-gated protocols ($p>0.05$) as shown in Table 3.

All quantitative measurements of image quality are given in Table 3. For the analysis of image quality, most of the measurements did not show significant differences in terms of CT attenuation, image noise, SNR and CNR between different anatomical locations, regardless of CT scanners and CCTA protocols ($p>0.05$). Only image noise measurements in DSCT with use of retrospective ECG-gated protocol were significantly different between aorta versus RCA (25.6 HU vs. 38.3 HU) and aorta versus LCA (25.6 HU vs. 35.6 HU) ($p<0.05$).

Radiation dose comparison

In prospective ECG-triggered groups using DSCT and SSCT protocols, the mean DLP was 249.3 ± 109.7 mGy·cm and 238.3 ± 37.9 mGy·cm corresponding to an effective dose estimation of 6.5 ± 2.9 mSv and 6.2 ± 1.0 mSv, respectively, with no significant difference between these two protocols ($p=0.99$). Whereas in the retrospective ECG-gated groups using DSCT and SSCT protocols, the mean DLP was 699.5 ± 318.9 mGy·cm and 1088.5 ± 269.8 mGy·cm corresponding to an effective dose estimation of 18.2 ± 8.3 mSv and 28.3 ± 7.0 mSv, respectively, resulting in significant difference between these two protocols (Figure 3). However, estimation of effective doses was lower by 35% with application of 0.017 mSv·mGy⁻¹·cm⁻¹ conversion coefficient factor when compared to that with use of 0.026 mSv·mGy⁻¹·cm⁻¹ (Table 4). With regard to effective dose comparison in genders, none of the results were significantly different between males and females (Figure 4). In the prospective ECG-triggered group, the effective dose was slightly higher in males than in females with the use of DSCT (6.7 ± 3.0 mSv vs. 6.2 ± 2.7 mSv) ($p=0.28$) and SSCT scanners (6.3 ± 0.8 mSv vs. 6.1 ± 1.2 mSv) ($p=0.07$). In the retrospective ECG-gated group, the effective dose was similarly higher in males than in females with the use of SSCT (29.4 ± 7.5 mSv vs. 27.2 ± 6.4 mSv) ($p=0.22$). On the other hand, the effective dose estimation in females was greater than in males with the use of DSCT scanner (20.4 ± 9.2 mSv vs. 16.3 ± 7.1 mSv) ($p=0.16$), despite no significant difference being reached.

The correlation between effective doses and patients' BMI was tested with Pearson correlation and this resulted in a strong positive linear correlation for SSCT with prospective ECG triggering ($r=0.64$), SSCT with retrospective ECG gating ($r=0.65$) and DSCT with retrospective ECG gating ($r=0.62$). However, the prospective ECG-triggered group with DSCT showed weak positive linear correlation ($r=0.11$). All these correlations are presented in Figure 5.

Discussion

This study demonstrates two main findings which are useful for clinical study. Firstly, there was no significant difference in image quality between prospective ECG-triggered and retrospective ECG-gated CCTA regardless of the use of SSCT or DSCT scanner. All images were presented with sufficient quality in more than 96% of the coronary segments. Secondly, prospective ECG-triggered CCTA leads to a significant lower radiation dose compared to with a retrospective ECG-gated technique performed with both DSCT and SSCT techniques.

Prospective ECG-triggered CCTA has been widely used in the diagnosis of CAD since it provides a lower radiation dose. This method has since been evaluated for image quality of the coronary arteries and for diagnostic accuracy as well as effective radiation dose in several studies [14-18]. Studies comparing prospective triggering with retrospective gating have shown that prospective triggering resulted in high image quality with lower percentage of suboptimal images [16,25]. Earl *et al* conducted a comparative study of 121 patients using prospective triggered CCTA examinations with 82 patients on retrospective ECG-gated CCTA [25]. They found out that image quality was significantly improved with prospective triggering with low percentage of non-evaluable segments (1.4% for prospective and 2.1% for retrospective gated CCTA). Shuman *et al* also showed similar results that the coronary segments with unadjusted chest size were likely to have a better image quality score in prospective triggering than in retrospective gating ($p=0.03$). However, when adjusted by comparing patients with the same chest size, the score of image quality was not significantly different between prospective triggering and retrospective ECG gating, but 77% lower patient dose was achieved with prospective triggering when compared with that of retrospective gating [16]. Although prospective ECG-triggered CCTA with SSCT in our study resulted in the highest score of excellent image quality (44.3%), the percentage of insufficient image

quality was still high (3.4%) compared to retrospective gating (1.8%). Similar findings were noted with prospective triggering (1.8%) compared to retrospective gating using DSCT (0.8%). This is because the heart rate was elevated unexpectedly during data acquisition in some cases using prospective ECG-triggered protocol. The presence of inadequate ECG synchronization caused severe stair-step artefacts which led to poor image quality. Our results are similar to those of a previous study [14], where the non-assessable coronary segments were higher in the prospective triggering (2.6%) than in the retrospective ECG gating (0.9%).

It has been reported that prospective ECG triggering using single-source 64-slice CT scanners substantially reduced radiation doses with sufficient image quality of the coronary arteries [18, 25, 26]. The major disadvantage of the prospectively triggered method is the limited predefined interval for data acquisition (normally in the mid-diastole phase). Therefore, only reconstructed images from a single phase of the cardiac cycle are available for diagnostic interpretation to represent the entire coronary artery segments. In patients with higher heart rate (>70 bpm), image reconstruction is set in the systolic phase to ensure diagnostic image quality. In our study, beta-blockers were used in patients with higher heart rate (>65 bpm) in order to minimize risk of non-diagnostic image quality for prospective ECG triggering. **Apart from beta-blockers, ivabradine can also be used as an alternative to reduce heart rate. Oral ivabradine has been reported to be a safe and effective heart rate lowering agent when compared to the beta-blockers, according to a recent study [27].** However, if the heart rate cannot be controlled after administration of heart rate lowering drugs, the scan is reverted to retrospective **gated** protocol. This is because small heart rate irregularities might lead to stair-step artefacts. Previous studies have found a significant correlation between average heart rate and cardiac motion artefact and also between heart rate variability and stair-step artefacts

[14,28]. Less heart rate variability has been reported in CCTA using contrast agents with lower osmolarity compared to higher osmolarity contrast agents [29]. Other than heart rate restriction, prospective ECG-triggered technique could not provide information on ventricular or valvular function. Again, a retrospective ECG-gated procedure should be obtained to meet the purpose.

In comparison with SSCT, DSCT is advantageous because CCTA can be undertaken in patients with higher or even irregular heart rates such as atrial fibrillation. This is due to the improvement of temporal resolution at 83 ms in DSCT, which allows the pitch to increase by up to 0.5 at increased heart rates ranging from 70 to 100 bpm without affecting image quality [30]. Another advantage of DSCT is that it produces lower radiation dose than SSCT in retrospective gated protocol [31]. This was confirmed in our study as the effective dose recorded with DSCT (18.2 mSv) was significantly lower than with SSCT (28.3 mSv).

The available data have shown that effective dose in females was significantly higher than in males in retrospective ECG-gated CCTA [32, 33], however, the impact of sex on dose reduction associated with prospective ECG-triggered compared to retrospective ECG-gated CCTA between DSCT and SSCT has not been addressed. Results of this study indicate that radiation dose did not differ significantly between genders in prospective ECG-triggered CCTA. The dose difference between males and females was observed in retrospective ECG-gated CCTA, which is consistent with a recent report by Esposito et al [34].

The latest conversion coefficient factor (E/DLP) was used in this study to accurately estimate the effective dose for CCTA examination, which represents a unique aspect of this study. The E/DLP value that is specific for coronary CT examinations has not been widely used in the literature [22]. The current practices assume that the E/DLP used in coronary CT were similar to that used for chest CT examinations (0.014 or $0.017 \text{ mSv}\cdot\text{mGy}^{-1}\cdot\text{cm}^{-1}$) [23,35,36].

However, this is considered inadequate as the estimation does not reflect the measurement at the cardiac region. Therefore, the E/DLP value of $0.026 \text{ mSv} \cdot \text{mGy}^{-1} \cdot \text{cm}^{-1}$ was applied in this study since this value was likely to be more accurate for estimation of radiation dose associated with cardiac CT compared to the chest CT [22]. The reason for the update is because the cardiac region is likely to be more radiosensitive than the chest, which results in E/DLP ratios. Moreover, the tissue weighting factor in the breast has been reported in ICRP-103 and it changed significantly from 0.05 to 0.12 [22,23]. These changes have led to an increase in effective dose of about 35% compared to the E/DLP value for averaged chest CT examinations. We admit that the estimation of effective dose calculation for CCTA based on the new conversion coefficient factor value is much higher than that calculated with the current approach, but it is of paramount importance to apply the timely relevant factor according to the latest publication of the ICRP tissue weighting factor.

Although our analysis of radiation dose reduction using the above-described strategies is reasonable and sufficient since it combines both qualitative and quantitative methods, we acknowledge several limitations in our work. Firstly, our comparative study used two different CT scanners from different manufacturers. Therefore, certain features might vary significantly in both types of scanners such as power output availability and technical parameters setting. Secondly, we did not investigate the diagnostic accuracy in the detection of CAD in both prospective and retrospective ECG-gated groups, neither in SSCT nor in DSCT because most patients did not undergo invasive coronary angiography examinations. Lastly, although low tube voltage (100 kV) was applied in some subgroups (prospective ECG-triggered and retrospective ECG-gated CCTA with use of DSCT) for dose comparison, results were not presented in the present study due to inhomogeneity of patients group.

In conclusion, prospective ECG-triggered CCTA reduces radiation dose significantly compared to retrospective ECG-gated CCTA, while maintaining good image quality. Although prospective ECG triggering provides no significant difference in radiation dose between both types of scanners, DSCT is advantageous since it results in lower percentage of insufficient image quality as compared to SSCT. Taking into account the advantages and disadvantages of the different techniques, the following guidelines for the selection of different CCTA protocols are recommended: in patients with slow and regular heart rate a protocol with prospective ECG triggering should be chosen, whereas in patients with higher or irregular heart rate retrospective ECG gating should be considered.

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The authors of this manuscript have certified that they have complied with the Principles of Ethical Publishing in the *International Journal of Cardiology* [37].

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Figure legends

Figure 1. Flow chart showing the administration of beta-blocker.

Figure 2. The quantitative measurement was obtained by locating the region of interest (ROI) at the root of the ascending aorta (a), perivascular fatty tissue (b), left main coronary artery (c) and proximal right coronary artery (d). If image quality was scored 2 or more, ROI was placed at the area where artefacts were least severe.

Figure 3. Box plot shows the mean effective dose estimation reported in the studies with use of 64-slice single-source CT (SSCT) and 64-slice dual-source CT (DSCT) with prospective and retrospective ECG-gated CCTA. Effective dose estimated in SSCT with retrospective ECG-gated CCTA is the highest amongst all of the four groups. The box indicates the first to third quartiles, with the line in the box indicating median quartile, and whiskers indicate the minimum and maximum values. The estimation of effective dose was calculated based on $0.026 \text{ mSv}\cdot\text{mGy}^{-1}\cdot\text{cm}^{-1}$ conversion coefficient factor.

Figure 4. Box plot shows the mean estimation of effective dose comparison between genders in SSCT and DSCT with prospective and retrospective ECG-gated CCTA. The box indicates the first to third quartiles, with the line in the box indicating the median quartile, and whiskers indicate the minimum and maximum values. The estimation of effective dose was calculated based on $0.026 \text{ mSv}\cdot\text{mGy}^{-1}\cdot\text{cm}^{-1}$ conversion coefficient factor.

Figure 5. Graph shows correlation analysis of effective dose estimation depending on body mass index (BMI) for prospective (a) and retrospective (b) ECG-gated CCTA groups. In prospective gating, a strong positive correlation was shown only in SSCT ($r=0.64$) while in DSCT this resulted in a weak positive correlation ($r = 0.11$). However, in the retrospective ECG gating, both SSCT and DSCT showed a strong positive correlation with $r=0.65$ and

$r=0.62$, respectively. The estimation of effective dose was calculated based on $0.026 \text{ mSv}\cdot\text{mGy}^{-1}\cdot\text{cm}^{-1}$ conversion coefficient factor.