Chulalongkorn Medical Journal

Volume 64
Issue 3 *July 2020*

Article 3

7-1-2020

Assessment of radiation dose in cardiac CT angiography using retrospective ECG gating technique at Ramathibodi Hospital (P. 237)

Saifhon Admontree

Sawwanee Asavaphatiboon

Napapong Pongnapang

Anchali Krisanachinda

Chula Med J Vol. 64 No. 3 July - September 2020; 237-245 DOI : 10.14456/clmj.2020.30

Original article

Assessment of radiation dose in cardiac CT angiography using retrospective ECG gating technique at Ramathibodi Hospital

Saifhon Admontree[a], Sawwanee Asavaphatiboon [b], Napapong Pongnapang [c], Anchali Krisanachinda[d,*]

[a]*Advanced Diagnostic Imaging Center (AIMC), Faculty of Medicine, Ramathibodi Hospital, Mahidol University, Bangkok, Thailand*
[b]*Department of Radiology, Faculty of Medicine, Ramathibodi Hospital, Mahidol University, Bangkok, Thailand*
[c]*Department of Radiological Technology, Faculty of Medical Technology, Mahidol University, Bangkok, Thailand*
[d]*Department of Radiology, Faculty of Medicine, Chulalongkorn University, Bangkok, Thailand.*

Background: The value of 320-detector CT is the volumetric imaging of the entire heart in a single heartbeat per one gantry rotation. The 64-detector- based spectral detector computed tomography (SDCT) uses two layers of detectors to concomitantly accumulate high and low energy data that differentiate materials of different effective atomic numbers. The Cardiac CT Angiography (CTA) has become a reliable diagnostic noninvasive modality used for evaluating the coronary artery disease, along with the advances of CT technology; they need to be concerned in radiation dose.

Objectives: The purpose of this study was to evaluate the radiation dose and establishing local Diagnostic Reference Levels (DRLs) in Cardiac CT Angiography between wide beam detector (320-detector CT) and 64-spectral detector CT (SDCT) using retrospective ECG gating technique.

Methods: A retrospective consecutively analysis of Cardiac CTA by retrospective ECG gating technique in 83 patients from 320-detector CT and 22 patients from spectral detector CT were evaluated. In the105 patients, there were 43 males and 62 females; their age ranged 16 - 91 years, mean age 64.5 ± 11.8 years, and average body mass index (BMI) was 26.77 kg/m^2. Conversion factor (f = 0.014 mSv/mGy.cm) was applied to estimate the effective dose (E) from dose length product (DLP) in this study.

Results: Mean of $CTDI_{vol}$ (mGy), DLP (mGy.cm) and effective dose (mSv) of calcium scoring for 320-detector were: 8.1 ± 3.2, 118.9 ± 48.3, 1.7 ± 0.7; and the 75th percentile values were:10.7, 148.1, 2.1; and Cardiac CTA using retrospective ECG gating technique (in average z-axis coverage of 15 ±1.2 cm) were: mean 35.1 ± 37 / 468.1 ± 303.9/ 6.6 ± 4.3, the 75th percentile values 39.3/579.3/8.1. For 64-SDCT (in average z-axis overage of 13.8 ± 1.3 cm), the mean $CTDI_{vol}$/ DLP/ effective dose of calcium scoring were: 4.2 ± 0/57.5 ± 5.8/0.8 ± 0.08; and, the 75th percentile values were: 4.2/58.8/0.8; Cardiac CTA were: 45.7 ± 11.8/785.1 ± 235/11.1 ± 13.2 and the 75th percentile values were 52.6/879.7/12.0. Coronary artery bypass graft evaluation was routinely performed on 320-detector CT. As the results of average z- axis coverage was 36.6 cm, leading to highly mean and 75th percentile of $CTDI_{vol}$/ DLP/ effective dose were as follows: 28.2 ± 12.5/1068.8 ± 513.8/15 ± 7.2, 30.7/1375.6,19.3 mGy/mGy.cm/mSv, respectively.

Conclusions: The radiation dose was significantly lower in Cardiac CTA using retrospective ECG gating technique patients who underwent 320-detector CT although the mean z-axis coverage is larger than 64-spectral detector CT. Due to 320-detector CT enable volumetric imaging of entire heart within one cardiac cycle and 100 kV_p has been used. While as 64-spectral detector CT 120 kV_p has been used for dual energy and several heartbeats acquired to capture the entire heart.

Keywords: Spectral detector CT, 320-detector CT, radiation dose, cardiac CT Angiography, retrospective ECG gating technique.

***Correspondence to: Anchali Krisanachinda,** Department of Radiology, Faculty of Medicine, Chulalongkorn University, Bangkok 10330, Thailand. Email: anchali.kris@gmail.com
Received: April 19, 2019
Revised: June 28, 2019
Accepted: July 15, 2019

Multi-detector computed tomography (MDCT) has rapidly evolved from 4-detector row systems in 1998 to 256-slice and 320-detector row CT systems. With smaller detector element size and faster gantry rotation speed, spatial and temporal resolutions of the 64-detector MDCT scanners have made coronary artery imaging a reliable clinical test. Since the advent of 64-detector row computed tomography (CT) in 2005, coronary computed tomographic angiography (CTA) has been demonstrated as a promising noninvasive technique for the evaluation of coronary artery stenosis. (1 - 2) The introduction of 64- and 320-MDCT, coronary CT angiography (CTA) has become a reliable diagnostic imaging modality for the assessment of coronary artery disease (CAD) because of its noninvasive nature. Wide-area coverage MDCT (320-detector CT), has enabled volumetric imaging of the entire heart free of stair-step artifacts at the diastolic phase of R-to-R interval within one cardiac cycle and improve greater diagnostic accuracy of CT coronary angiography. (3)

In recent years, rapid advances in cardiac CT technology, with the progress of conventional single-energy computed tomography (SECT) to dual- energy computed tomography (DECT) or spectral detector computed tomography (SDCT) (4) have been reported. The principles of DECT base strongly on energy-dependence attenuation of materials because the photoelectric effect is highly dependent on the atomic number (Z) of the considered tissues, and it plays an important role in spectral CT material characterization. The 64-spectral detector CT scanner was classified to the type of a single source that takes advantage of the polychromatic nature of the x-ray beam, and a single scan is performed at a high energy. (5) The highly specialized detectors consist of two scintillator layers that have maximal sensitivity for different x-ray photon energies. A top or first layer of low atomic number (Z) of yttrium-based garnet detector preferentially absorbs the low energy photon, by design approximately 50 percent of the total incident photon flux. A layer of gadolinium oxysulphide (Gd_2O_2S) in the bottom or second layer absorbs the remaining high-energy photon. The excellent temporal registration of spectral detector CT well suited for material decomposition in the projection domain also perfect spatial registration of acquired data to create the complete spectral dataset. (4 - 6)

The greatly improved temporal and spatial resolution, cardiac CT encompasses a wide range of new clinical applications. Visualization of coronary arteries is probably the most challenging CT task, as it requires excellent temporal resolution to reduce motion artifacts caused by the beating heart, and a high spatial resolution to differentiate small coronary structures. These requirements pose a much higher demand for radiation dose than non-cardiac CT imaging. (3, 7, 8) The purposes of this study were to evaluate the radiation dose and to establish local Diagnostic Reference Levels (DRLs) in Cardiac CT Angiography between wide beam detector (320-detector) and 64-spectral detector CT using retrospective ECG gating technique.

Materials and methods

The patient radiation dose obtained from Toshiba Aquilion ONE 320-detector CT scanner and Philips IQon 64-Spectral detector CT scanner at Advanced Diagnostic Imaging Center (AIMC), Faculty of Medicine, Ramathibodi Hospital, Mahidol University had been collected. The CT systems had been installed in 2010 and 2016, respectively. The quality control of both CT scanners were performed prior collecting the patient data, in order to verify the volume CT Dose Index ($CTDI_{vol}$, units: mGy) values on the CT monitor console.

The proposal on patient data collection including scanning parameters from picture archiving and communication system (PACS) of the hospital was approved by the Institutional Review Boards (IRB) of Ramathibodi Hospital, Mahidol University. All adult patients requested for Cardiac CT Angiography using retrospective ECG gating technique in 2017 were studied; the exclusion criterion was prospective ECG gating technique. Dose-Length Product (DLP, units: mGy. cm) is an indicator of the mean absorbed dose to the patient of each series in CT exam and defined as the product of $CTDI_{vol}$ and the scan length. The International Commission on Radiation Protection (ICRP) publication introduced the concept of effective dose (E; in mSv). The multiplication of the DLP and the conversion coefficient (f, 0.014mSv/(mGy•cm) for chest regions resulted in the effective dose of Cardiac CTA. (2, 9, 10)

The acquisition protocol of Cardiac CT angiography requires intravenous injection of an iodinated contrast media to differentiate the blood from the surrounding tissues and maximize opacification of the coronary arteries and left heart. The purpose to enhance the peak of contrast media in the short time of acquiring ECG- gating data, the high power dual-head injector was used to allowing a high injected flow rate of 5 – 6 milliliter (mL) per second. The high iodinated concentration of 370 milligrams per milliliter was chosen to increase the photoelectric effect in high atomic number (Z) of iodine material. Intravenous catheter placement at antecubital fossa in the right-side injections with an 18-gauge catheter was performed to avoid streak artifact occurred in the superior field of view from the transit of the contrast bolus across the left brachiocephalic vein. [11] Bolus tracking technique was utilized to automatically initiated detect the optimal time to scan the arrival contrast-enhanced heart, in the region of interest with 170 Hounsfield unit (HU). A region of interest (ROI) was placed in the descending aorta at the level of mid axial volume of scan and tracheal bifurcation for 320-detector CT and 64-spectral detector CT, respectively.

During the ECG- data acquisition the patient needs to breath-holding to avoid gross displacement of the heart and improve image quality. [12] The coronary calcium scoring scanning should be performed before the cardiac CT angiographic study to evaluate the risk of coronary artery disease from calcified and make sure that patient can cooperate during the scan.

The scanning protocols used for Cardiac CT Angiography (CTA) both in 320-detector and 64-spectral detector CT are shown in Table 1. The automatic exposure control (AEC) of both scanners automatically adapts the x-ray tube current to the overall patient size to achieve a specified level of image quality. [13]

Results

The parameters of 105 patients, who underwent in Cardiac CTA by retrospective ECG gating technique for evaluating coronary artery disease, were collected from PACS of Ramathibodi Hospital (83 patients from 320-detector CT, and 22 patients from 64-spectral detector CT). Among the 105 patients, 43 were males and 62 females, their age ranged 16 - 91 years: their mean age 64.3 years and average body mass index (BMI) of the patient in the study was 26.77 kg/m^2. The mean and the third quartile or 75th percentile values of $CTDI_{vol}$, DLP, and effective dose of calcium scoring and Cardiac CTA by retrospective ECG gating technique are shown in Table 2.

From Table 2, mean and the 75th percentile values of $CTDI_{vol}$/ DLP/ effective dose of calcium scoring and Cardiac CTA using retrospective ECG gating technique were as follows: 8.1 ± 3.2, 118.9 ± 48.3, 1.7 ± 0.7, 10.7/148.1/2.1; 35.1 ± 37 / 468.1 ± 303.9 / 6.6 ± 4.3, 39.3/579.3/8.1 for 320-detector CT (in average z-axis coverage of 15 cm) and 4.2 ± 0/57.5 ± 5.8/0.8 ± 0.08, 4.2/58.8/0.8; 45.7 ± 11.8/785.1 ± 235/ 11.1 ± 13.2, 52.6/879.7/12 for 64-spectral detector CT (in average z-axis coverage of 13.8 cm), respectively. The coronary artery bypass graft evaluation was routinely performed on 320-detector CT. As the result of average z-axis coverage was 36.6 cm, leading to highly mean and 75th percentile of $CTDI_{vol}$/ DLP/ effective dose were 28.2 ± 12.5/1068.8 ± 513.8/15 ± 7.2, and 30.7/1375.6/ 19.3 mGy/mGy.cm/mSv, respectively. The results are shown in Figures 1 - 3.

Table 1. Scanning parameters used for cardiac CT Angiography protocols in 320-detector and 64-spectral detector CT using retrospective ECG-gating technique.

Scanning parameters	320-detector CT	64-spectral detector CT
Scan mode type	Axial (sequential) scan	Spiral (helical) scan
Beam collimation (mm)	320 x 0.5 (160 mm z-coverage)	64 x 0.625 (40 mm z-coverage)
Coverage area	Coronary CTA : Tracheal bifurcation to apex of heart Coronary artery bypass graft evaluated: Apex to base of lung	
Reconstructed slice thickness/ increment (mm)	0.5 /0.25	0.9/0.45
Rotation time (milliseconds)	350	270
Temporal resolution (milliseconds)	175	135
Approximately scan time or Exposure time (seconds)	Less than 3	8-10
Kilovoltage peak (kV_p)	100	120
ECG-based tube current modulation	Yes	Yes
Automatic exposure control	SURE Exposure 3D (CTA Volume SD 33)	Dose Right Cardiac 35
Average total mAs (Range)	Coronary CTA : 476 (144-867) CABG evaluated: 2847 (1662-5635)	514 (265-813)
Pitch	Not applicable	0.16

Table 2. Mean and the 75th percentile values of $CTDI_{vol}$, DLP and effective dose of coronary calcium scoring and cardiac CTA in retrospective ECG- gating technique.

Acquisition protocols	CT scanner	Mean ± SD z-coverage: cm (Range)	Radiation dose: Displayed CTDI:mGy (Range) Mean ± SD	Displayed CTDI:mGy 75th percentile	DLP: mGy.cm (Range) Mean ± SD	DLP: mGy.cm 75th percentile	Effective dose : mSv (Range) Mean ± SD	Effective dose : mSv 75th percentile
Coronary calcium scoring	320-detector	14.9	8.1 ± 3.2 (3.4 - 18.4)	10.7	118.9 ± 48.3 (47 - 293.9)	148.1	1.7 ± 0.7 (0.7 - 4.1)	2.1
	64-spectral detector	13.5	4.2 ± 0	4.2	57.5 ± 5.8 (50.4 - 67.2)	58.8	0.8 ± 0.08 (0.7 - 0.9)	0.8
Coronary CTA	320-detector	15 ± 1.2 (12 - 16)	35.1 ± 37 (5.9 - 293.9)	39.3	468.1 ± 303.9 (95.2-1732.1)	579.3	6.6 ± 4.3 (1.3 - 24.3)	8.1
	64-spectral detector	13.8 ± 1.3 (11.8 - 15.9)	45.7 ± 11.8 (24.4 - 73.5)	52.6	785.1 ± 235 (414 - 1404)	879.7	11.1 ± 13.2 (5.8 - 19.7)	12.0
Coronary artery bypass graft	320-detector	36.6	28.2 ± 12.5 (6.7 - 51)	30.7	1068.8 ±513.8 (270.9 - 2233.1)	1375.6	15 ± 7.2 (3.8 - 31.3)	19.3

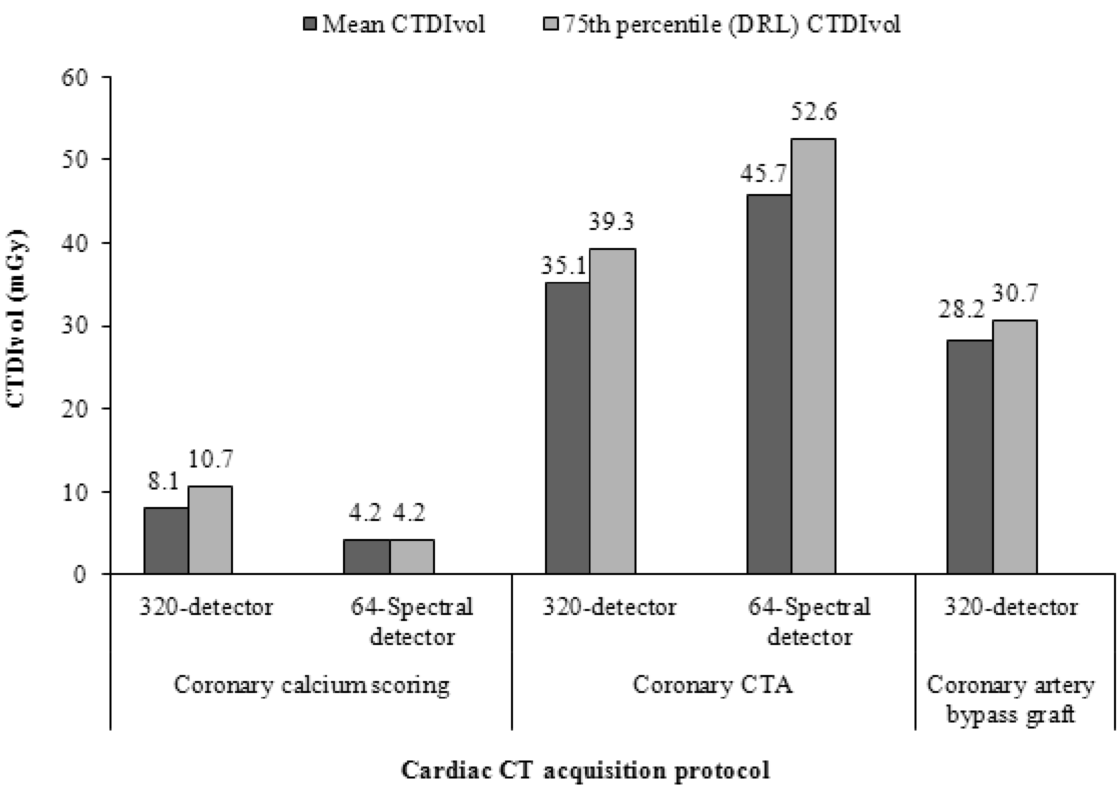

Figure 1. Mean and the 75th percentile values of $CTDI_{vol}$ of coronary calcium scoring, Cardiac CTA and coronary artery bypass graft using retrospective ECG gating technique for 320-detector and 64-spectral detector CT.

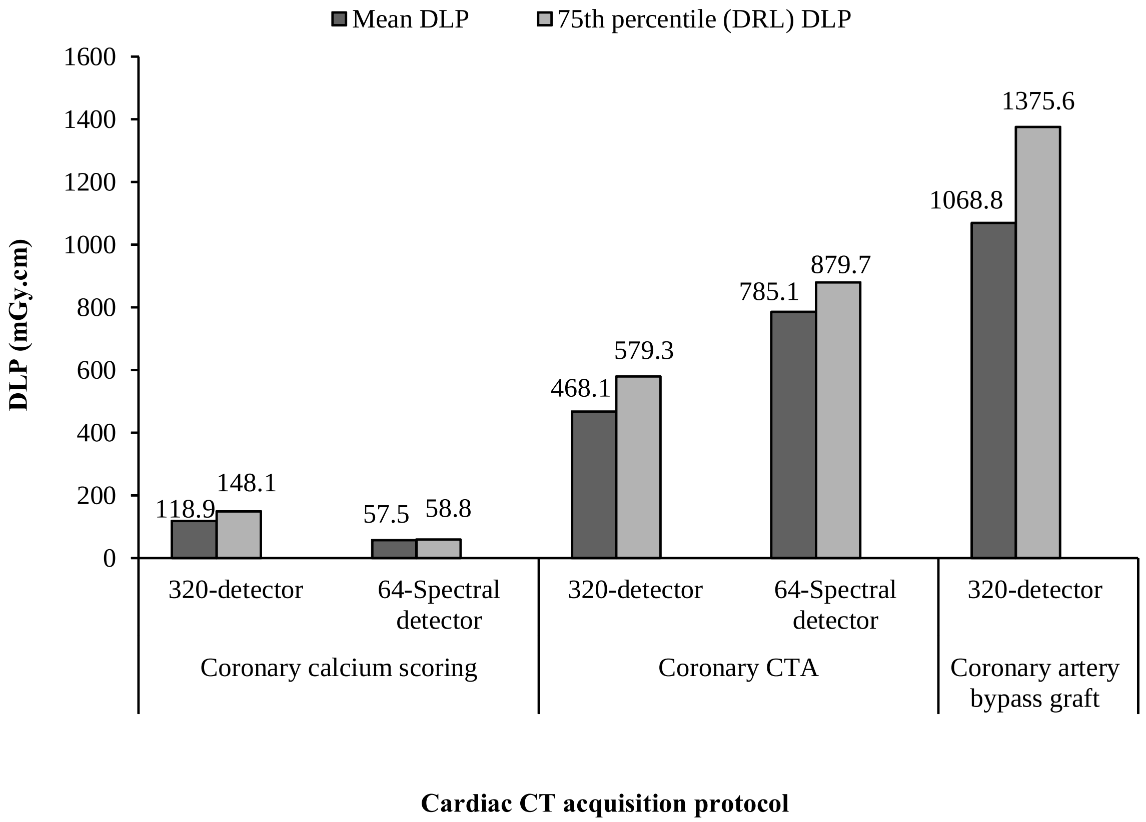

Figure 2. Mean and the 75th percentile values of DLP of coronary calcium scoring, Cardiac CTA and coronary artery bypass graft using retrospective ECG gating technique for 320-detector and 64-spectral detector CT.

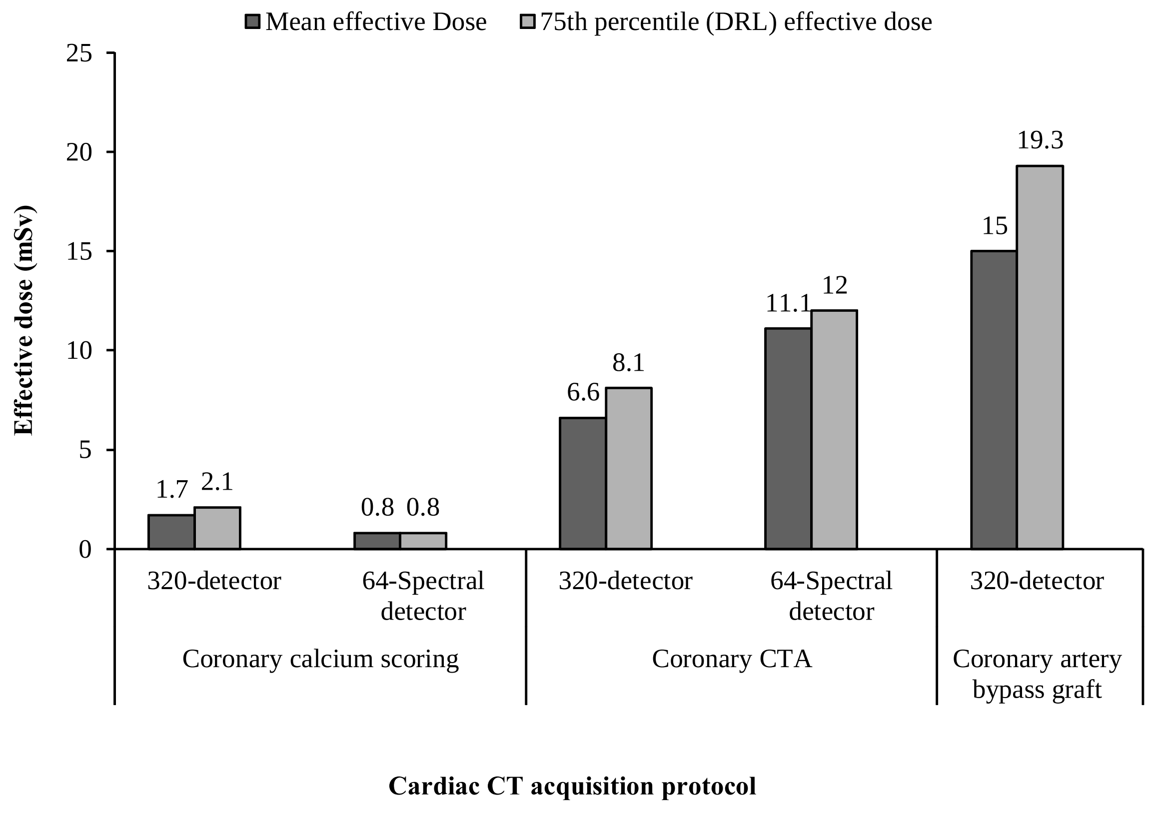

Figure 3. Mean and the 75th percentile values of effective dose of coronary calcium scoring, Cardiac CTA and coronary artery bypass graft using retrospective ECG gating technique for 320-detector and 64-spectral detector CT.

Discussion

The patient radiation dose received during cardiac CTA examination varies substantially, and characterizes among the scanner type, patient body size and the scan protocol. Without dose saving measures, the dose of a 64-slice CT coronary angiogram varies between 8 and 20 mSv. [12] The patient radiation doses in this study and reference dose data in cardiac CTA are shown in Table 3.

The mean effective dose of retrospective ECG gating technique in 64-spectral detector CT in this study is similar to another retrospective ECG gating technique in 64-single source and dual-source MDCT but higher than Khan study in prospective ECG gating technique of 320-detector CT. Retrospectively ECG-gated helical scanning mode is commonly used in cardiac CT due to its clinical flexibility. Moreover, a significant dose-reduction technique is ECG tube-current pulsing, which involves modulating the tube current down to 4.0 – 20.0% of the full tube current for phases that are of minimal interest. [3]

The third quartile or 75th percentile (local DRLs) of $CTDI_{vol}$ and DLP, among this study and others in cardiac CTA are shown in Table 4. $CTDI_{vol}$ at 45 mGy and DLP at 686 mGy.cm in this study were comparable to other studies; considering similar data collection method, as expected, our results were higher than prospective ECG- gating method and the study with similar method. In comparison to the Asian population such as in Japanese, the $CTDI_{vol}$ in this study is lower approximately two times, according to the modern CT technology in coronary CTA. On the other hand, this study is the lowest in retrospective ECG- gating method, while as in the lower border range when considering in mixed mode. The variation in radiation dose was mainly on: the exposure parameters, type of ECG- gating method to acquire image data and body mass index of patient data.

Although the patient data collection is small leading to the limitation in statistical strength, this is the pilot study, the radiation dose is suitable to optimize coronary CTA protocol focusing on the establishment of local DRLs.

The radiation dose of coronary calcium scoring protocol in 320- detector CT is higher than 64-spectral CT although almost the same scanning parameters with 120 kV_p and conventional acquisition mode were used because the mean range in z-axis coverage of 14.9 cm is longer than 13.5 cm. The radiation dose of Cardiac CTA by retrospective ECG gating technique in patients who underwent 320- detector CT was significantly lower approximate two times despite of the mean z-coverage is larger than 64-spectral detector CT due to, volumetric imaging of whole heart and coronary vessels can be imaged within a single heartbeat and 100 kV_p was used in 320- detector CT. While as several heartbeats were acquired to capture the entire heart and 120 kV_p was used for the benefit of tissue decomposition analysis, leading to high radiation dose in 64-spectral detector CT.

In practical, the selection of the patient for each CT scanner depends on clinical indication and image quality including applications need. [32] Meanwhile, in order to reduce radiation dose, the 320-detector CT scanner was chosen for young patients.

Table 3. Mean effective dose in this study compared to similar international studies report in cardiac CTA with 320- and 64- detector CT.

Cardiac CTA study	Type of ECG gating technique	Number of detector row/ Coverage in z- direction (Range: mm)	Mean Effective Dose (mSv)
This study	Retrospective	320-detector CT /120 - 160 (150)	6.6
	Retrospective	64-specral detector CT/ 118 - 159 (137)	11.1
Khan A, *et al.*[2]	Prospective	320-detector CT /120 - 160	4.4
Rybicki FJ, *et al*.[14]	Prospective	320-detector CT /160	7.2
Baumuller S, *et al*.[15]	Retrospective	64-Dual-Source CT	10.9
	Retrospective	64-MDCT	10.4
Rixe J, *et al*.[16]	Retrospective	64-Dual-Source CT	11.4
	Retrospective	64-MDCT	8.6
Hirai N, *et al*.[17]	Retrospective	64-MDCT	20
	Prospective	64-MDCT	4.1

Table 4. The 75th percentile (DRLs) of $CTDI_{vol}$ and DLP, among this study and other references established data in cardiac CTA.

Cardiac CTA study	ECG- gating mode	$CTDI_{vol}$ (mGy)	DLP (mGy.cm)
This study (2018)	Retrospective (320-detector CT)	40	580
	Retrospective (64- SDCT)	53	880
	Retrospective (320 and 64-detector CT)	45	686
Castellano IA, *et al*. (United Kingdom, 2017) (18, 19)	n/a	n/a	173
Danish Health Authority (Denmark, 2015) (18, 20)	n/a	29	230
Alhailiy AB, *et al*. (Australia, 2018) (21)	Prospective	22	268
German Federal Office for Radiation Protection (Germany, 2016) (18, 22)	n/a	20	330
Van der Molen AJ, *et al*. (Netherland, 2013) (18, 23)	n/a	n/a	671
B□rdyov□ Z, *et al*. (Slovakia, 2018) (24)	Mixed mode	43	509
Mafalanka F, *et al*. (France, 2014) (25)	Prospective	26	370
	Retrospective	44	970
Alhailiy AB, *et al*. (Saudi Arabia, 2018) (26)	Prospective	24	393
	Retrospective	46	1057
	Mixed mode	43	808
Treier R, *et al*. (Switzerland, 2010) (18, 27)	n/a	50	1000
Hosseini Nasab SMB, *et al*. (Iran, 2016) (28)	Mixed mode	67	1073
Palorini F, *et al*. (Italy, 2014) (18, 29)	n/a	61	1208
Japan Network for Research and Information on Medical Exposures (Japan, 2015) (18, 30)	n/a	90	1400
Fukushima Y, *et al*. (Japan, 2012) (18, 31)	n/a	n/a	1510

Note: (n/a) The data did not show in published data.

The patient dose reduction in Cardiac CTA should be considered by means of rigorous scan coverage that fits to the heart or according to the clinical consideration, tube voltage reduction to increase the photoelectric effect of contrast medium and tissue, anatomical tube current modulation, iterative reconstruction algorithm, ECG- tube current modulation and prospectively triggered CT angiography in case of stable low heart rate. The most benefit in this study is the patient dose monitoring, indicating the radiation dose values for the local diagnostic reference levels, DRLs for optimization tool strategies at our facility.

Conclusion

The mean and 75th percentiles of effective dose in Cardiac CTA by retrospectively ECG gating technique at Ramathibodi Hospital were 6.6 and 8.1 mSv for 320-detector, and 11.1 and 12.0 mSv for 64-spectral detector CT, respectively. As the valuable of 320-detector CT is volumetric imaging of the entire heart in a single heartbeat per one gantry rotation and the specificity of spectral detector CT uses two layers of detectors to differentiate materials of different effective atomic numbers, the decision of modality used mainly depends on the clinical indications considered by the radiologist.

Conflict of interest

The authors, hereby, declare no conflict of interest.

References

1. Danad I, Fayad ZA, Willemink MJ, Min JK. Recent advances in cardiac computed tomography: dual energy, spectral and molecular CT Imaging. JACC Cardiovasc Imaging 2015;8:710-23.
2. Khan A, Khosa F, Nasir K, Yassin A, Clouse ME. Comparison of radiation dose and image quality: 320-

MDCT versus 64-MDCT coronary angiography. AJR Am J Roentgenol 2011;197:163-8.
3. Yu L, Liu X, Leng S, Kofler JM, Ramirez-Giraldo JC, Qu M, et al. Radiation dose reduction in computed tomography: techniques and future perspective. Imaging Med 2009;1:65-84.
4. Forghani R, De Man B, Gupta R. Dual-energy computed tomography: Physical principles, approaches to scanning, usage, and implementation: Part 1. Neuroimaging Clin N Am 2017;27:371-84.
5. Romman Z, Uman I, Yagil Y, Finzi D, Wainer N, Milstein D. Detector technology in simultaneous spectral imaging [Internet].2014 [cited 2018 Apr 20]. Available from: http://clinical.netforum.healthcare.philips.com/us_en/Explore/White-Papers/CT/Detector-technology-in-simultaneous-spectral-imaging.
6. Altman A. State of the art and future trends in radiation detection for computed tomography [Internet].2019 [cited 2019 Apr 20] Available from: www.aapm.org/education/vl/vl.asp?id=2325.
7. Wang M, Qi HT, Wang XM, Wang T, Chen JH, Liu C. Dose performance and image quality: dual source CT versus single source CT in cardiac CT angiography. Eur J Radiol 2009;72:396-400.
8. International Commission on Radiological Protection. Radiological protection and safety in medicine. A report of the International Commission on Radiological Protection. Ann ICRP 1996;6:1-47.
9. Deak PD, Smal Y, Kalender WA. Multisection CT protocols: sex- and age-specific conversion factors used to determine effective dose from dose-length product. Radiology 2010;257:158-66.
10. International Commission on Radiological Protection. The 2007 Recommendations of the International Commission on Radiological Protection. ICRP publication 103. Ann ICRP 2007;37:1-332.
11. Rogers IS, Truong QA, Joshi SB, Hoffmann U. Cardiac computed tomography. In: Dilsizian V, Pohost GM, editors. Cardiac CT, PET and MR. 2nd ed. Chichester, West Sussex: Wiley Blackwel; 2010. p.72-94.
12. Nieman K. MSCT coronary imaging. In: Dilsizian V, Pohost GM, editors. Cardiac CT, PET and MR. 2nd ed. Chichester, West Sussex: Wiley Blackwell; 2010. p. 246-58.
13. American Association of Physicists in Medicine. CT scan parameters: Translation of terms for different manufacturers [Internet]. 2012 [cited 2018 Apr 20]. Available from: https://www.aapm.org/pubs/CTProtocols/documents/CTTerminologyLexicon.pdf.
14. Rybicki FJ, Otero HJ, Steigner ML, Vorobiof G, Nallamshetty L, Mitsouras D, et al. Initial evaluation of coronary images from 320-detector row computed tomography. Int J Cardiovasc Imaging 2008;24: 535-46.
15. Baum□ller S, Leschka S, Desbiolles L, Stolzmann P, Scheffel H, Seifert B, et al. Dual-source versus 64-section CT coronary angiography at lower heart rates: comparison of accuracy and radiation dose. Radiology 2009;253:56-64.
16. Rixe J, Conradi G, Rolf A, Schmermund A, Magedanz A, Erkapic D, et al. Radiation dose exposure of computed tomography coronary angiography: comparison of dual-source, 16-slice and 64-slice CT. Heart 2009;95:1337-42.
17. Hirai N, Horiguchi J, Fujioka C, Kiguchi M, Yamamoto H, Matsuura N, 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.
18. Damilakis J, Frija G, Hierath M, Jaschke W, Mayerhofer-Sebera U, Paulo G, et al. European study on clinical diagnostic reference levels for X-ray medical imaging. ENER/D3/2016-282. Brussels, Belgium: European Commission; 2018.
19. Castellano IA, Nicol ED, Bull RK, Roobottom CA, Williams MC, Harden SP. A prospective national survey of coronary CT angiography radiation doses in the United Kingdom. J Cardiovasc Comput Tomogr 2017;11:268–73.
20. Danish Health Authority. Ct Referencedoser. Copenhagen: Danish Health Authority; 2015.
21. Alhailiy AB, Ekpo EU, Ryan EA, Kench PL, Brennan PC, McEntee MF Diagnostic. reference levels for cardiac CT angiography in Australia. Radiat Prot Dosimetry 2018;182:525-31.
22. Schegerer AA, Nagel HD, Stamm G, Adam G, Brix G. Current CT practice in Germany: Results and implications of a nationwide survey. Eur J Radiol 2017; 90:114–28.
23. van der Molen AJ, Schilham A, Stoop P, Prokop M, Geleijns J. A national survey on radiation dose in CT in The Netherlands. Insights Imaging 2013;4:383–90.
24. B□rdyov□ Z, Horv□thov□ M, Nikodemov□ D. Estimation of diagnostic reference levels for CT coronarography in Slovakia. Radiat Prot Dosimetry 2018;181:310-6.
25. Mafalanka F, Etard C, Rehel JL, Pesenti-Rossi D, Amrar-Vennier F, Baron N, et al. Establishment of diagnostic reference levels in cardiac CT in France: a

need for patient dose optimisation. Radiat Prot Dosimetry 2015;164:116-9.
26. Alhailiy AB, Kench PL, McEntee MF, Brennan PC, Ryan EA. Establishing diagnostic reference levels for cardiac computed tomography angiography in Saudi Arabia. Radiat Prot Dosimetry 2018;181:129-34.
27. Treier R, Aroua A, Verdun FR, Samara E, Stuessi A, Trueb PR. Patient doses in CT examinations in Switzerland: implementation of national diagnostic reference levels. Radiat Prot Dosimetry 2010;142: 244–54.
28. Hosseini Nasab SMB, Shabestani-Monfared A, Deevband MR, Paydar R, Nabahati M. Estimation of cardiac CT angiography radiation dose toward the establishment of national diagnostic reference level for CCTA in Iran. Radiat Prot Dosimetry 2017;174: 551–7.
29. Palorini F, Origgi D, Granata C, Matranga D, Salerno S. Adult exposures from MDCT including multiphase studies: First Italian nationwide survey. Eur Radiol 2014;24:469–83.
30. Japan Network for Research and Information on Medical Exposures. Diagnostic reference levels based on latest surveys in Japan – Japan DRLs 2015. Kyoto: J-RIME; 2015.
31. Fukushima Y, Tsushima Y, Takei H, Taketomi-Takahashi A, Otake H, Endo K. Diagnostic reference level of computed tomography (CT) in Japan. Radiat Prot Dosimetry 2012;151:51–7.
32. Rajiah P, Abbara S, Halliburton SS. Spectral detector CT for cardiovascular applications. Diagn Interv Radiol 2017;23:187-93.