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Research article

Coronary CT angiography radiation dose trends: A 10-year analysis to develop institutional diagnostic reference levels

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ABSTRACT

Purpose: To develop institutional diagnostic reference levels (IDRL) for coronary CT angiography (CCTA) according to patient size by analyzing radiation dose changes over the past 10 years.

Materials and methods: This IRB approved retrospective investigation analyzed radiation dose data from CCTA between 2007 and 2016 at our institution. Annual trends in radiation dose were described for each scanner type and scanning mode. Radiation levels were analyzed for normorhythmic patients, patients with prior coronary artery bypass grafting (CABG), arrhythmia, and according to patient size and tube voltage. Median, and quartile values for volume CT dose index (CTDIvol), dose-length product (DLP), and size-specific dose estimate (SSDE) were calculated. Wilcoxon rank-sum test and Kruskal Wallis test were performed to assess the significance of quantitative data.

Results: 35,375 examinations from 33,317 patients (median age, 58 [50–66] years; male patients, 21,087 [58.7%]) were analyzed. CTDIvol, DLP, and SSDE significantly decreased by 9.0%, 30.8%, and 40.1% (all $P < 0.05$) for all examinations, respectively. All radiation dose metrics progressively decreased across scanning modes (especially retrospectively ECG-gated spiral and prospectively ECG-triggered high-pitch spiral acquisition mode), but did not significantly change across scanners in the last 6 years. CTDIvol and DLP increased with patient size when water-equivalent diameters were > 19 cm for normorhythmic and CABG patients. In arrhythmic patients, CTDIvol increased progressively with water-equivalent diameters across all groups.

Conclusion: CCTA radiation dose has progressively decreased in the past decade except in patients with prior CABG and arrhythmia. Size-specific IDRLs may optimize radiation utilization in these patients going forward.

1. Introduction

Coronary CT angiography (CCTA) has become a useful and commonly applied diagnostic tool for the detection of coronary artery disease (CAD) [1]. The widespread use of CCTA has brought improvements to the diagnosis of heart disease both in the emergent and elective settings, patient risk stratification, as well as subsequent management. Since the early 1980s, radiation exposure from medical imaging has increased up to six-fold [2]. Due to the inherent difficulty of cardiac imaging, it does not come by surprise that cardiovascular imaging studies and image-guided interventions are responsible for almost 40% of all medical-related radiation exposure [2], which has raised health concerns [3,4]. However, CT has made significant strides in recent years in reducing radiation dose. Many techniques have been adopted to reduce CCTA radiation dose, including automated tube voltage and current selection, prospectively ECG-triggered and high-pitch scan acquisitions, and iterative reconstruction methods [5–9].

Diagnostic reference levels (DRL) are set standards based on scan type (e.g. organ of interest) used to monitor radiation exposure and identify situations where radiation exposure is elevated [10]. By using the DRL concept, radiation dose reduction techniques can be identified and implemented. The institutional diagnostic reference level (IDRL) is often defined as the 75th percentile of radiation dose prescribed at an institution [11]. Achievable dose (AD) is defined as the 50th percentile

Abbreviations: IDRL, institutional diagnostic reference levels; CCTA, coronary CT angiography; CABG, coronary artery bypass grafting; CTDIvol, volume CT dose index; DLP, dose-length product; SSDE, size-specific dose estimate

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radiation exposure and provides a standard for comparison when scanners are upgraded or protocols are optimized. Ideally, this value should decrease over time as new technologies emerge and radiation dose reduction techniques are adopted [12].

DRLs based on individual size may allow facilities to optimize protocols according to different patient sizes in order to avert unnecessary radiation exposure. Yet, only one threshold value for a single examination type was provided by previously developed national DRLs. These values were established according to a phantom [12], uniform patient size [13], or averaged size from all patients [14].

Since national or institutional DRL derived from CCTA are thus insufficiently established, the purpose of this study was to develop IDRLs for CCTA according to patient size by analyzing the changes in radiation dose over the past 10 years.

2. Materials and methods

2.1. Patient demographic and radiation dose data collection

This retrospective study was approved by our institutional review board and granted a waiver of informed consent. Data from patients who received a CCTA in our institution from 2007 to 2016 were collected for this study. CCTA examinations performed on either a first or second-generation dual-source CT scanner (SOMATOM® Definition or SOMATOM® Definition Flash, Siemens Healthineers, Forchheim, Germany) were included in this investigation. All data were transferred to the Radimetrics® Enterprise Platform, version 2.5b (Bayer HealthCare, Whippany, NJ USA), an automated dose-monitoring and analyzing software which collects and computes radiation dose data from the Radiation Dose Structured Report stored on PACS [15]. Patients younger than 18 years old were excluded from the analysis. Studies with missing patient information such as age and study date, dose indices, study description, and scanning mode were excluded from this cohort. Studies that had no water equivalent diameter or that included multiple body organs were excluded, so as to avoid radiation dose overestimation.

2.2. Quality control analysis

Patient-, age-, and gender-dependent frequency distribution of examinations were described per year. All CCTA data were classified according to the scanner type used (1st versus 2nd generation DSCT), and scanning mode (retrospectively ECG-gated spiral acquisition mode, prospectively ECG-triggered sequential acquisition mode, or prospectively ECG-triggered high-pitch spiral acquisition mode ["High-Pitch" mode]).

2.3. Radiation dose analysis

Changes in total radiation dose during the study period were analyzed first. Radiation dose distribution was then studied according to heart rhythm (normorhythmic versus arrhythmic), surgical history of coronary artery bypass grafting (CABG) regardless of heart rhythm, scanner type, scanning mode, tube voltage, and patient size.

The water-equivalent diameter method, which was calculated from the automatically determined anteroposterior diameter and lateral thickness, according to the methods promulgated by the American Association of Physicists in Medicine (AAPM), was used to assess patient size [16,17]. Patient size was categorized into 4-cm water-equivalent diameter categories. Those categories were constructed by using the distribution of the data and by keeping the clinical practical usefulness in mind. Dose metrics summarized by the software and presented in this study were comprehensive [18], including volume CT dose index (CTDIvol) in mGy, dose-length product (DLP) in mGy cm, and water-equivalent size-specific dose estimate (SSDE) in mGy. CTDIvol reflects the average dose of sweep volume using a specific phantom (32-cm acrylic cylindrical phantom). DLP is calculated by multiplying CTDIvol and scan length. Water-equivalent SSDE is calculated from CTDIvol using appropriate conversion factors [19] determined by patient size, which is more accurate than conventional SSDE [16,20,21]. For all these metrics, 25th, 50th (median), and 75th percentile values were reported. The AD and the IDRL were defined as the 50th and 75th radiation dose percentiles achieved, respectively.

2.4. Statistical analysis

All data were analyzed by Statistical Product and Service Solutions (SPSS) software (IBM SPSS, version 19, SPSS Inc. Chicago, IL, USA). Patient gender and youth (i.e., age < 45 years) were described as values and percentiles. Patient age and radiation dose parameters (CTDIvol, DLP and SSDE) were described as medians and inter-quartile range [M (QU-QL)]. Wilcoxon rank sum test was performed for comparing radiation doses between the two scanner types. Kruskal Wallis tests were performed for radiation dose comparison between different tube voltages, different scanning modes, clinical indications, and years. Correlation analysis was used for z-axe coverage and radiation dose. Presence of a monotonically increasing or decreasing trend was tested with the nonparametric Mann-Kendall test. *P* values < 0.05 were considered statistically significant.

3. Results

3.1. Patient demographics

From 2007 to 2016, all data form 35,450 CCTA examinations (33,388 patients were collected. A total of 75 (0.2%) examinations were excluded for: age < 18 years old (n = 41), missing CT protocol details (n = 19), missing radiation dose parameters (n = 9), missing gender information (n = 5), and missing water-equivalent diameter information (n = 1). The remaining 35,375 examinations (including 311 [0.9%] examinations of patients with a history of CABG and 1233 [3.5%] examinations of arrhythmic patients) from 33,317 (including 21,087 [58.7%] males) patients were included in the final analysis Table 1. The median age of patients was 58 years, which remained constant when averaged yearly (p = 0.07). In addition, the ratio of younger patients (< 45 years old) undergoing CCTA examinations did not vary significantly (from 11.8% to 15.3%) during ten years (p = 0.86).

3.2. Quality control analysis

Supplementary Table 1 shows CT scan parameters associated with CCTA examinations across different patient groups and all

Table 1
Demographics of patients and scan parameters included over the entire study duration and for specific years.

Year	Median patient age (y)	Total no. of examinations	Total no. of patients	Total no. of male patients	Total no. of female patients	Percentage of patients < 45 y (%)
2007	58	1179	1128	740	388	13.0%
2008	57	1469	1379	896	483	15.8%
2009	58	2221	2017	1252	765	14.2%
2010	58	2892	2623	1856	1037	12.4%
2011	58	3510	3227	1871	1356	15.0%
2012	58	4352	3990	2259	1731	13.7%
2013	58	4434	4208	2371	1837	13.6%
2014	58	4989	4745	2752	1993	14.9%
2015	58	5255	5056	2940	2116	14.9%
2016	59	5075	4944	2889	2055	13.0%
Total	58	35375	33317	19556	13761	14.1%

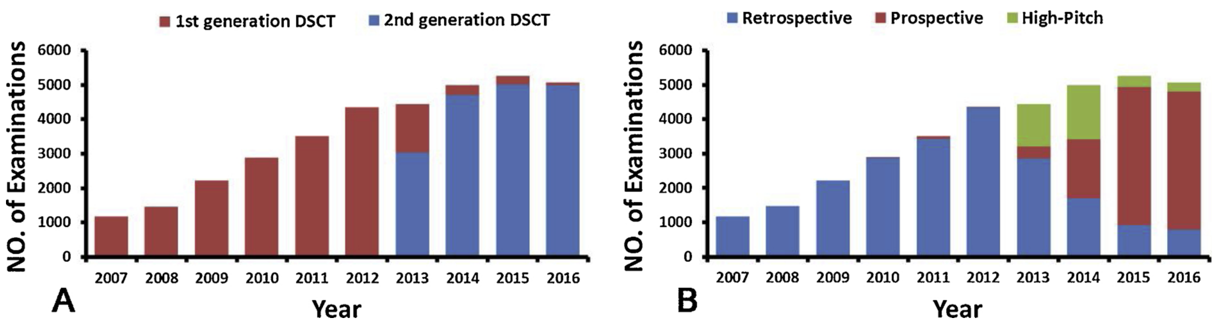

Fig. 1. Graphs show the yearly numbers of all examinations according to (A) scanner type and (B) scanning mode.
Since 2013, the use of 2nd generation dual-source CT (DSCT) for CCTA progressively increased. During that same time period, the use of prospectively ECG-triggered sequential acquisitions also progressively increased.

examinations. Since 2013, the use of 2nd generation dual-source CT for CCTA at our hospital progressively increased whereas the use of the 1st generation scanner substantially decreased. After 2013, 2nd generation dual-source CT became the preferred instrument for CCTA, accounting for more than 50% of investigations every year (Fig. 1A). Additionally, since 2013, prospectively ECG-triggered sequential acquisitions for CCTA examinations progressively increased while retrospectively ECG-gated spiral acquisitions markedly decreased. High-pitch spiral CCTA examinations accounted for less than 10% of scans during the study period (Fig. 1B). Supplementary Fig. 1 show the number of examinations per year by CT scanner type and scanning modes for normorhythmic patients, CABG patients, and arrhythmic patients, respectively.

3.3. Total radiation dose

The overall median CTDIvol, DLP, SSDE values were 47.4 mGy [25.1–61.1 mGy], 661.2 mGy cm [315.2–940.0 mGy cm], 66.9 mGy [38.5–97.3 mGy]. From 2007–2016, the radiation dose increased during the first three years, then reached a plateau phase (all $p > 0.05$), and decreased during the final 5 years (all $p = 0.01$) as shown in Fig. 2. In that period (from 2012 to 2016), median CTDIvol, DLP, and SSDE significantly decreased by 63.8%, 72.5%, and 63.4% (from 64.4 mGy [56.1–72.1 mGy], 980.4 mGy cm [851.9–1146.6 mGy cm], and 89.3 mGy [77.4–104.2 mGy] to 23.3 mGy [15.8–33.0 mGy], 269.9 mGy cm [183.8–402.8 mGy cm], and 32.7 mGy [23.0–45.8 mGy]) (all $P < 0.05$), respectively. Median CTDIvol, DLP and SSDE in 2016 (23.3 mGy [15.8–33.0 mGy], 269.9 mGy cm [183.8–402.8 mGy cm] and 32.7 mGy [23.0–45.8 mGy]) were significantly lower than those in 2007 (25.6 mGy [21.0–48.2 mGy], 390.2 mGy cm [293.4–712.8 mGy cm] and 54.6 mGy [43.0–94.6 mGy]) (all $p < 0.05$), which decreased by 9.0%, 30.8% and 40.1%, respectively. Radiation dose trends were further analyzed according to heart rhythm (normorhythmic versus arrhythmic) and history of CABG as shown in Supplementary Fig. 2. The median radiation dose of normorhythmic patient examinations followed a similar trend to that of the overall radiation dose. The median radiation dose of CABG patients varied but reached its lowest level in 2016, achieving low dose as that seen with normorhythmic patients. However, the median radiation dose of arrhythmic patient examinations remained consistently elevated ($p = 0.06$).

Arrhythmic patients had median CTDIvol, DLP and SSDE values that were 114.7%, 132.6%, 128.2% higher than those in normorhythmic patients and 81.4%, 7.9%, and 78.2% higher than those in CABG patients (all $p < 0.05$) (Fig. 3).

3.4. Radiation dose from different scanner types and scanning modes

Comparisons of overall CTDIvol, DLP and SSDE according to scanner type and scanning mode are presented in Table 2 and Fig. 4. The median CTDIvol, DLP, and SSDE seen with 1st generation dual-source CT were 59.8 mGy [51.2–70.6 mGy], 909.7 mGy cm [763.0–1079.6 mGy cm] and 95.1 mGy [77.0–119.5 mGy], 116.7%, 165.2% and 141.4% higher than the values with 2nd generation dual-source CT (all $P < 0.05$), respectively. In the subsequent three years, all radiation dose metrics progressively decreased for 2nd generation dual-source CT and reached their lowest levels (23.1 mGy [15.7–32.4 mGy], 268.2 mGy cm [183.0–393.6 mGy cm], and 32.5 mGy [22.9–45.2 mGy]) in 2016, although they remained higher for 1st generation dual-source CT. The overall median CTDIvol for retrospectively ECG-gated spiral acquisitions was 57.9 mGy [47.2–59.0 mGy], approximately 116.9% and 185.2% higher than prospectively ECG-triggered sequential acquisitions and prospectively ECG-triggered high-pitch spiral CCTA examinations, respectively (all $P < 0.05$). The median radiation dose (CTDIvol, DLP, and SSDE) for prospectively ECG-triggered sequential and prospectively ECG-triggered high-pitch spiral acquisitions decreased progressively from 2014 to 2016, reaching the lowest levels of 22.8 mGy [16.2–30.8 mGy], 260 mGy cm [184.7–363.5 mGy cm], 32.1 mGy [23.2–42.7 mGy] and 3.3 mGy [2.3–3.6 mGy], 53.7 mGy cm [38.6–62.4 mGy cm], 4.5 mGy [3.5–5.0 mGy], decreasing by 28.5%, 33.8%, 30.2% and 89.0%, 85.1%, 89.7%, respectively (all $P < 0.05$), in 2016. In the first three years, the median CTDIvol of retrospectively ECG-gated spiral acquisitions rose progressively, and then decreasing gradually from 2009 to 2016 though with slight growth in some years.

Supplementary Figs. 3–5 and Supplementary Tables 2–4 show a comparison of CTDIvol, DLP and SSDE across the scanners and scanning

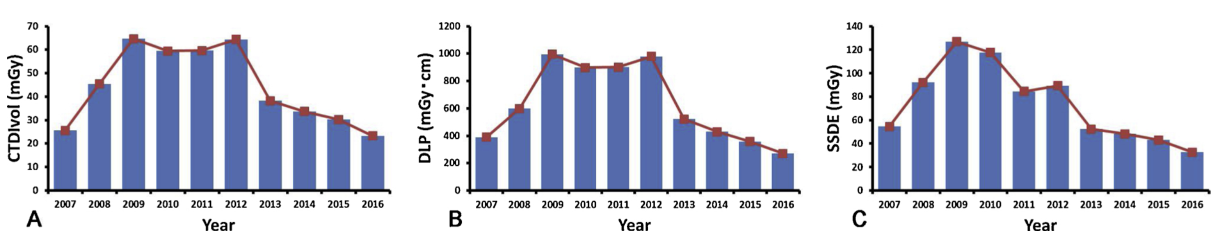

Fig. 2. Overall trend of median CTDIvol (A), DLP (B) and SSDE (C) from 2007 to 2016.
Radiation dose increased during the first three years, then reached a plateau phase, and decreased during the last 5 years.
DLP = dose-length product; CTDIvol = volume CT dose index; SSDE = size-specific dose estimate.

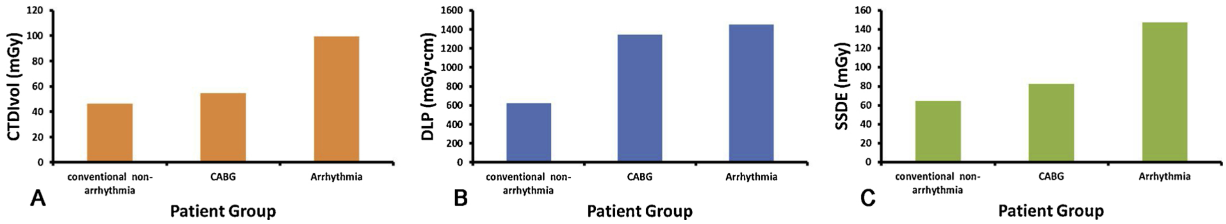

Fig. 3. Median CTDIvol (A), DLP (B) and SSDE (C) across different patient groups.
Arrhythmic patient examinations showed the highest radiation dose metrics, followed by patients with a history of CABG, and normorhythmic patient examinations. CABG = coronary artery bypass grafting; DLP = dose-length product; CTDIvol = volume CT dose index; SSDE = size-specific dose estimate

modes for normorhythmic, CABG, and arrhythmic patients. The radiation dose trend for normorhythmic patients was similar to that of the overall radiation dose. The differences remained significant for all radiation dose parameters between scanner types and scanning modes in normorhythmic patients and CABG patients (all $P < 0.05$). Except for SSDE of arrhythmic patients across the three scanning modes ($P = 0.829$), there were significant decreases in radiation dose between 1st and 2nd generation dual-source CT and across the three scanning modes (all $P < 0.05$).

3.5. Radiation dose from different tube voltages

Over the ten year study period, 5 different tube voltage settings (140 kVp, 120 kVp, 100 kVp, 80 kVp and 70 kVp) were used for CCTA examinations. In 2007, tube voltage was 120 kVp in all cases, while in 2016, 1948 of 5075 (38.4%) CCTA examinations used 120 kVp. The percentage of CCTA examinations using lower tube voltage (100 kVp, 80 kVp or 70 kVp) was 61.6% in 2016, which was higher than that in any other years. As tube voltage decreased from 140 kVp to 70 kVp, radiation dose was decreased significantly ($P < 0.05$). In the 140 kVp group, the median CTDIvol, DLP and SSDE were 62.7 mGy [44.9–71.4 mGy], 969.0 mGy cm [776.0–1165.2 mGy cm] and 77.5 mGy [59.8–113.6 mGy], much higher than those in the 70 kVp group (0.8 mGy [0.7-0.8 mGy], 14.5 mGy cm [13.3–15.7 mGy cm] and 1.1 mGy [1.0–1.1 mGy]) (all $P < 0.05$).

3.6. Radiation dose from different z-axe coverage

The median z-axes coverage from 2009 to 2012 (150.5, 150.5, 150.0 and 154.0 mm) were higher than that in any other years and decreased during the final 5 years. CABG patients had median z-axes coverage that was 71.1% higher than that in normorhythmic patients and 57.8% higher than that in arrhythmic patients (all $p < 0.05$) as shown in Supplementary Table 1. In the correlation analysis, CTDIvol, DLP, SSDE were positively correlated with z-axes coverage ($r = 0.288$, 0.467, 0.310, respectively; all $P < 0.05$).

3.7. Sized-based radiation dose

Water-equivalent diameter ranges along with corresponding number of examinations, AD, and IDRL (CTDIvol, DLP and SSDE) are listed in Table 3. Sized-based radiation dose distributions for normorhythmic, CABG, and arrhythmic patients are shown in Fig. 5. Among 33,831 examinations in normorhythmic patients, the median water-equivalent diameter was 25.6 cm. CTDIvol and DLP for IDRL were found to increase with size when it was greater than 19 cm; however the SSDE followed an opposite trend. Patients with a history of CABG and a water equivalent diameter < 19 cm had a median DLP greater than that of other groups except patients with a water equivalent diameter between 27 and 31 cm. Median CTDIvol and SSDE was greatest in patients with a water equivalent diameter less than 19 cm. CTDIvol and DLP for IDRL of these patients increased with patient size when water-equivalent diameters were > 19 cm, whereas in arrhythmic patients all parameters except SSDE were lower in the < 19 cm group compared with the others. Those patients' CTDIvol increased progressively with patient size across all groups, but SSDE decreased progressively with patient size. Fig. 6 shows examination frequency of three scanning modes in different water-equivalent diameter groups. Retrospectively ECG-gated spiral acquisitions were used in 6134 of 6255 (98.1%) CCTA examinations for normorhythmic patients when water-equivalent diameters were < 19 cm, and in 14,244 of 27,576 (51.7%) examinations when > 19 cm. The corresponding ratio for CABG and arrhythmic patients are 100% (61 of 61) vs. 78.4% (196 of 250) and 100.0% (207 of 207) vs. 95.9% (984 of 1026).

4. Discussion

The purpose of this study was to analyze the changes over time in radiation dose of CCTA in our institution during a 10-year period using automated analytic software and establish size based DRL. We found that the overall radiation dose decreased gradually from 2007 to 2016, with the increased use of advancing technology. Additionally, patient-size based IDRL and AD were determined, ultimately providing a reference for CCTA examinations.

Methods for deceasing radiation dose used in CCTA have developed

Table 2
Radiation dose values for all examinations according to scanner type and scanning mode.

Parameters		No. of patients	Median [Interquartile Range]		
			CTDIvol (mGy)	DLP (mGy cm)	SSDE (mGy)
scanner type	1st generation dual-source CT	16873	59.8 [51.2–70.6]	909.7 [763.0–1079.6]	95.1 [77.0–119.5]
	2nd generation dual-source CT	17216	27.6 [18.7–40.5]	343.0 [224.1–501.5]	39.4 [27.5–55.6]
scanning mode	Retrospectively ECG-gated mode	20753	57.9 [47.2–69.0]	872.3 [687.6–1052.2]	88.9 [68.3–113.9]
	Prospectively ECG-triggered mode	9967	26.7 [19.2–37.2]	311.7 [224.6–438.2]	37.5 [28.0–51.9]
	High-pitch spiral mode	3386	20.3 [3.4–34.4]	247.4 [55.6–424.7]	30.3 [4.6–48.9]

CTDIvol = volume CT dose index; DLP = dose-length product; SSDE = size-specific dose estimate.

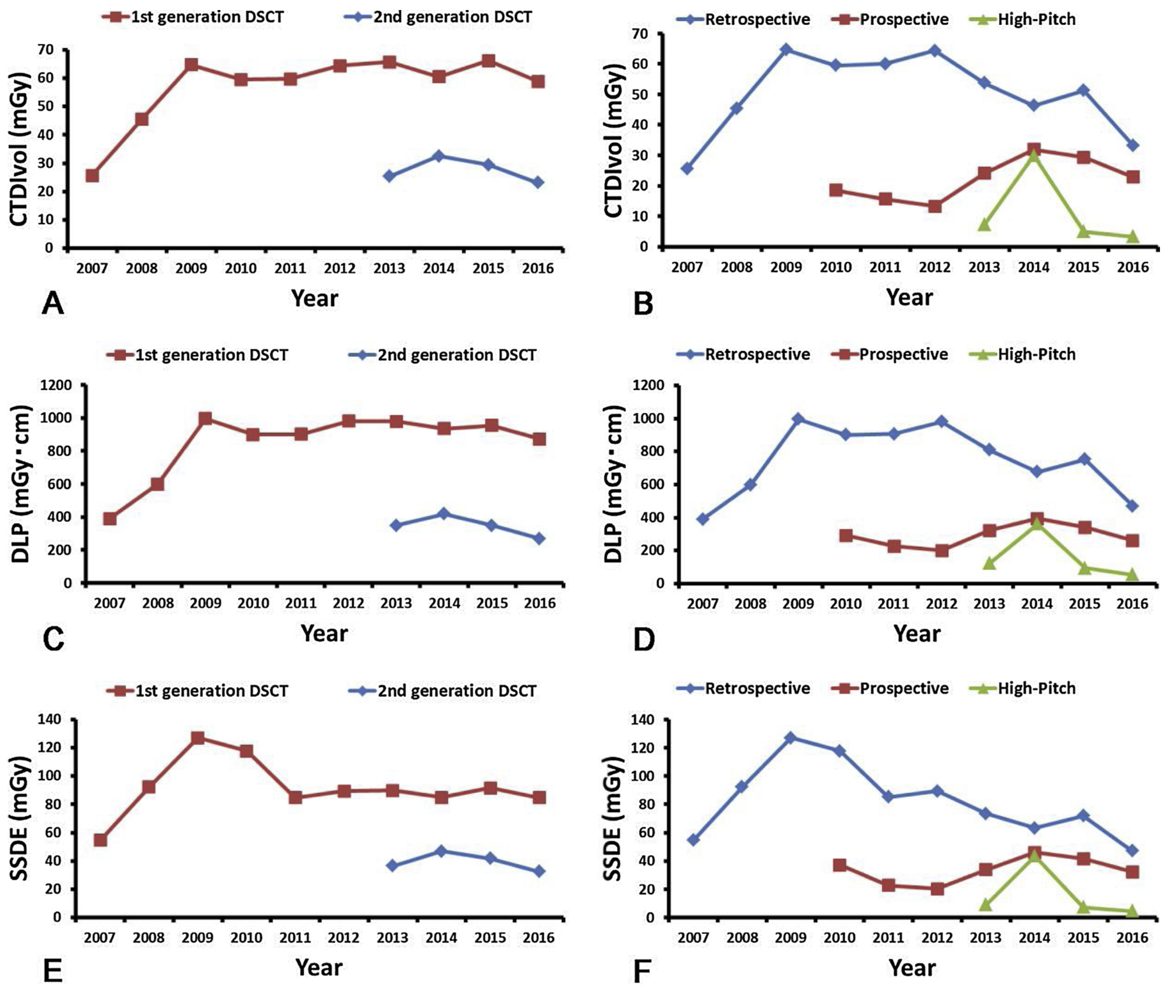

Fig. 4. Median CTDIvol, DLP and SSDE trends according to scanner type (A, C, E) and scan mode (B, D, F) from all examinations.
Radiation dose with 1st generation dual-source (DSCT) was higher than that with 2nd generation DSCT throughout the study period. At the beginning of 2011, radiation dose did not change significantly for 1st generation DSCT. From 2014 to 2016, the radiation dose decreased gradually with 2nd generation DSCT. In addition, the radiation dose of examinations performed with retrospective ECG-gating was the highest among the three scanning modes, although it decreased from 2012 to 2014. In 2016, the radiation dose of examinations performed in prospectively ECG-triggered high-pitch spiral modes reached their lowest levels.
CABG = coronary artery bypass grafting; DLP = dose-length product; CTDIvol = volume CT dose index; SSDE = size-specific dose estimate.

Table 3
Size-based ADs and IDRLs for normorhythmic, CABG, and arrhythmic patients.

Patients	Size (cm)	No. of examinations	CTDIvol (mGy)		DLP (mGy cm)		SSDE (mGy)	
			AD (Median)	IDRL (75th Percentile)	AD (Median)	IDRL (75th Percentile)	AD (Median)	IDRL (75th Percentile)
Normorhythmic	< 15	1919	52.7	60.6	783.6	947.1	118.3	136.1
	15-19	4336	55.3	63.9	813.1	971.2	111.4	128.9
	19-23	2563	23.4	55.1	318.4	861.9	39.2	92.6
	23-27	14486	34.4	57.2	435.2	865.7	49.9	82.8
	27-31	9858	49.4	61.8	663.7	917.1	64.1	81.1
	> 31	669	54.7	66.1	765.4	968.7	62.0	74.7
CABG	< 15	17	60.5	66.0	1374.8	1657.5	136.1	143.1
	15-19	44	60.8	72.2	1400.9	1574.8	120.2	140.3
	19-23	29	50.8	59.1	1286.0	1559.8	84.8	98.6
	23-27	135	52.8	64.0	1305.5	1587.3	77.8	91.3
	27-31	86	57.7	71.1	1383.0	1685.3	75.1	94.0
Arrhythmic	< 15	72	86.1	94.7	1296.0	1479.2	193.5	215.4
	15-19	135	91.6	99.4	1326.1	1445.3	179.8	196.4
	19-23	120	93.8	110.6	1478.1	1805.5	158.4	179.6
	23-27	511	100.5	110.6	1470.9	1685.7	149.3	161.7
	27-31	358	110.6	110.6	1509.1	1665.6	138.0	147.8
	> 31	37	110.6	122.0.	1552.6	1758.7	127.9	139.3

CABG = coronary artery bypass grafting; DLP = dose-length product; CTDIvol = volume CT dose index; SSDE = size-specific dose estimate.

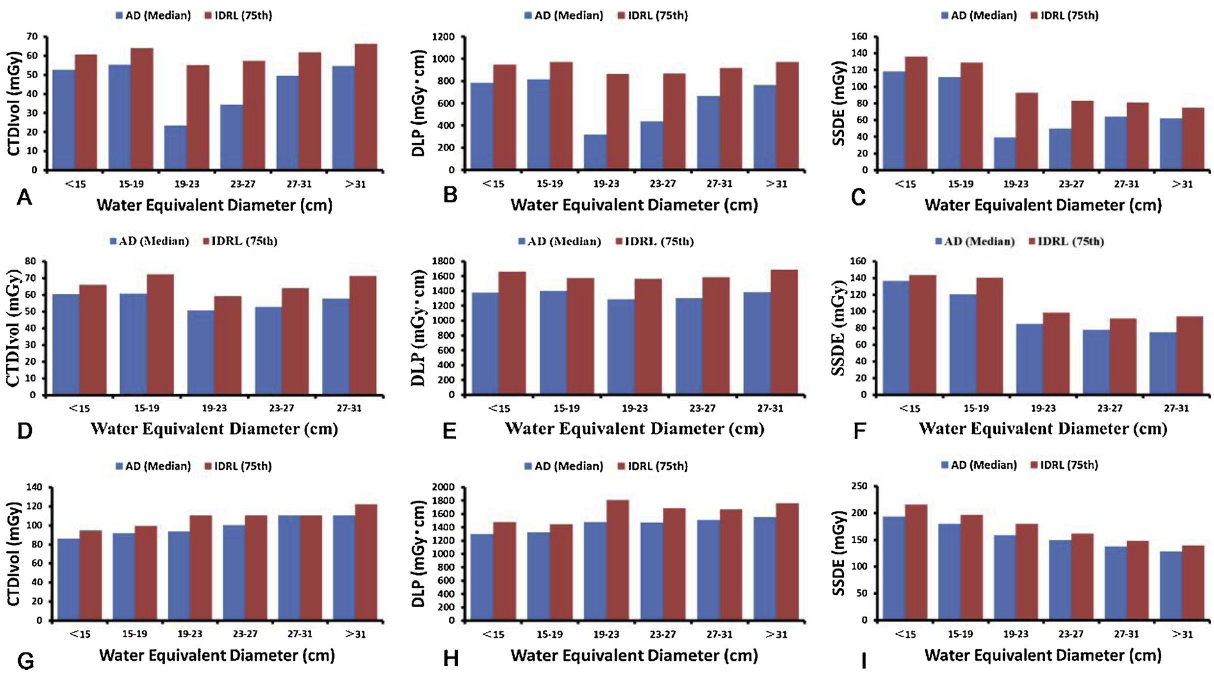

Fig. 5. Median and 75th CTDIvol, DLP and SSDE according to patient size for normorhythmic patients (A–C), patients with a history of CABG (D–F) and arrhythmic patients (G–I).

For normorhythmic and patients with previous CABG, CTDIvol and DLP increased with patient size when water-equivalent diameters were > 19 cm. For arrhythmic patients, CTDIvol and DLP increased progressively with patient size across all groups, but the SSDE decreased progressively with patient size.

AD = achievable dose; CABG = coronary artery bypass grafting; DLP = dose-length product; CTDIvol = volume CT dose index; SSDE = size-specific dose estimate

extensively in recent years. A decline in radiation dose of CCTA examinations in Germany from 2009 to 2014 was in accordance with our study [22]. This study differs from previous investigations [23–25] due to the number of examinations analyzed, and further decreased reference values. Tube voltage reduction, prospectively ECG-triggered [26] and high-pitch spiral scan acquisitions were all used in our study period, promoting overall radiation dose reduction from 2007 to 2016 [5,6]. By comparing radiation dose and proportion of different scanning modes, we conclude that the scanning mode constitutes an important factor in efforts to reduce radiation dose especially for normorhythmic patients. The observed radiation dose increase between 2009 and 2012 can be attributed to the prescription of broader ECG-dependent tube current modulation windows, during which full nominal tube current is applied, to ensure low image noise during cardiac motion nadirs. Our study found that radiation dose in CABG patients was the lowest in 2008, which was most likely due to the small number of cases (n = 2) and shorter mean scan z-coverage in that year. However, neither scanner type nor scanning mode caused obvious radiation dose reduction for CABG or arrhythmic patients in our study, which calls for greater efforts in radiation dose reduction specifically in these two patient categories going forward [27–31]. It has been reported [32] that the use of controlled tube current modulation resulted in a reduction of DLP of 25%, which have not analyzed in this study. In addition, as demonstrated by Hausleiter et al [32], the radiation dose of 64-slice system from Siemens was consistent with the findings in our study, which was higher than that from GE and Toshiba and lower than Philips. These findings demonstrate some potential for improving hardware and software reduce radiation dose.

The impact of patient size on radiation dose has already been established [33], but for general CT applications [34,35]. We further established size-based IDRLs and ADs for CCTA according to different indications and scanning modes. The IDRL in our study (55.1–66.1 mGy and 861.6–971.2 mGy cm) for normorhythmic patients was far lower than those for Japanese (90 mGy and 1400 mGy cm) using data from 2010 to 2015 [13], and ADs were usually less than IDRL. Improvement in protocols and scanners may be important factors for radiation dose reduction. However, comparison with data from the PROTECTION I study [32], where the CTDIvol (52.7 mGy) was lower but the DLP (885 mGy cm) was higher than those in our study, shows that the scan length should also be a focus of attention. A study in France [36] reported CTDIvol values of 26 and 44 mGy and DLP of 370 and 870 mGy cm for prospective and the retrospectively ECG-gated

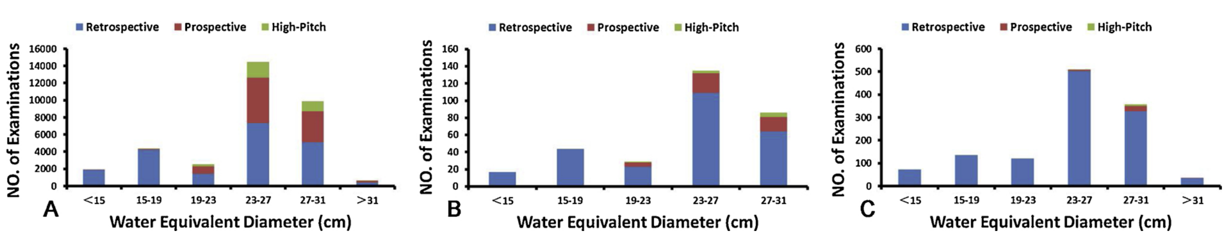

Fig. 6. Graphs show the examination frequency of different scanning modes across patient size for normorhythmic patients (A), patients with a history of CABG (B) and arrhythmic patients (C).

Regardless of indication, the ratio of retrospectively ECG-gated spiral acquisitions in patient size < 19 cm is higher than in patient size > 19 cm.

scanning mode, respectively, which were lower than those (CTDIvol of 37 and 69 mGy and DLP of 438 and 1052 mGy cm) in this study. Exclusion of radiation dose received from the calcium scoring scan acquisition in their dosimetric analysis likely constitutes one cause, as inclusion of the calcium scoring scan would have incurred an increase of 12% in DLP (from 1208 mGy cm to 1373 mGy cm). In addition, an IDRL based on patient specific parameters (i.e. CABG and arrhythmic patients) further enhances the granularity of the radiation dose standard. In our study, patients with a water-equivalent diameter < 19 cm had the highest median SSDE and higher CTDIvol and DLP than individual groups. This may be attributed to a higher ratio of retrospectively ECG-gated spiral acquisitions in this population than in other populations in our institution, which incurred overall radiation dose increases. As such, further investigations to establish an IDRL for small size patients is warranted.

There are several limitations to this study. First, the CCTA data were derived from only two scanner models at our institution and were relatively homogeneous. As a result, this DRL cannot easily be generalized to national or international levels with a more diverse scanner fleet. However, our institution is a large hospital in our geographic region, and based on this data from a ten-year period, the IDRL was determined. The data at different institutions will need to be analyzed to establish a more general DRL. The image quality was not analyzed nor did we specifically investigate the impact of iterative reconstruction, automated tube voltage selection, and automated anatomical tube current modulation, which were all used at our institution during the study period. Finally, this was an observational study with several optimization methods applied. Thus, any single one optimization strategy can not demonstrate radiation dose change. However, the application of all measures may be effective to optimize radiation use in daily practice, especially as institutional monitoring, benchmarking, and dose management are rationalized and facilitated by the increased availability of automated analytical software.

In conclusion, we found that the systematic use of advancing technological means for radiation reduction has enabled progressive decreases in radiation dose levels from CCTA in the past 10 years, although more efforts are warranted in patients with CABG and cardiac arrhythmia; moreover, a size-based IDRL for CCTA was developed.

Conflicts of interest

UJS is a consultant for and/or receives research support from Astellas, Bayer, GE, Guerbet, and Siemens Healthineers. The other authors have no conflicts of interest to declare.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ejrad.2019.02.012.

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