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## FULL PAPER

# The associated factors for radiation dose variation in cardiac CT angiography

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**Objective:** This study aimed to examine the associated factors for dose variation and influence cardiac CT angiography (CCTA) dose benchmarks in current CT imaging centres.
**Methods:** A questionnaire was distributed to CT centres across Australia and Saudi Arabia. All participating centres collected data for adults who underwent a CCTA procedure. The questionnaire gathered information about the examination protocol, scanning parameters, patient parameters, and volume CT dose index (CTDI vol) and dose–length product (DLP). A stepwise regression analysis was performed to assess the contribution of tube voltage (kV), padding time technique, cross-sectional area (CSA) of chest and weight to DLP.
**Results:** A total of 17 CT centres provided data for 423 CCTA examinations. The median $CTDI_{vol}$, DLP and effective dose were 18 mGy, 256 mGy.cm and 5.2 mSv respectively. There was a statistically significant difference in DLP between retrospective and prospective ECG-gating modes ($p = 0.001$). Median DLP from CCTA using padding technique was 61% higher than CCTA without padding ($p = 0.001$). The stepwise regression showed that kV was the most significant predictor of DLP followed by padding technique then CSA while patient weight did not statistically significantly predict DLP. Correlation analysis showed a strong positive correlation between weight and CSA ($r = 0.78$), and there was a moderate positive correlation between weight and DLP ($r = 0.42$), as well as CSA and DLP ($r = 0.48$).
**Conclusion:** Findings show radiation dose variations for CCTA. The associated factors for dose variation found in this study are scanning mode, kV, padding time technique and CSA of the chest. This results support the need to include CSA measurements in future dose survey and for setting DRLs.
**Advances in knowledge:** The study provides baseline information that helps to understand the associated factors for dose variations and high doses within and between centres performing CCTA.

## INTRODUCTION

Cardiac CT angiography (CCTA) is now one of the important diagnostic imaging tool for coronary artery disease (CAD).[1] Despite numerous technological innovations in dose saving technologies in current CT scanners, radiation doses from procedures using ionising radiation can be linked to a possible carcinogenic risk to patients.[2] Recent epidemiological evidence demonstrates that cancer incidence rates in imaged paediatric patients increase after CT exposure.[3] Also, flow cytometry methods have for the first time demonstrated damage activation of the repair pathways in cells at dose as low as 7.5 mSv.[4] Although this is not direct evidence of cancer development, it is direct evidence of damage to DNA at diagnostic dose levels. Thus, concerns about doses from procedures using ionising radiation are valid and highlight the need for continuous optimisation so that the risk from the examination is minimised.

Diagnostic reference levels (DRLs) are used to self-identify high dose medical imaging protocols and facilitate the implementation of methods to lower dose in clinical practice.[5–8] DRLs surveys provide baseline data allowing CT facilities to compare their dose levels with national and international benchmarks, enabling them to trigger optimisation strategies when their facility doses exceed the recommended level. A recent review shows noticeable variations in CCTA local DRLs (LDRLs) values within and between CT centres,[9] however there is a lack of understanding of the associated factors for these dose variations. It is important that the design and implementation of practical dose management approaches is supported by detailed

understanding of potential factors responsible for high doses and dose variations.

Body size is major factor in patient dose. Particularly, in CCTA examination, as obese patients tend to have a higher prevalence of CAD.[10] It is important to note that obese individuals do not necessarily have a large chest diameter, and people of normal weight may have a large chest diameter.[11] Research conducted by Zarb et al[12] showed that the correlation between the chest diameters [anteroposterior (AP) and transverse] and CT dose is stronger than the relationship between weight and CT dose. However, current DRLs methodologies rely on average weight as the only indicator of body size, whereas size measurements such as cross-sectional area (CSA) of the chest are not widely used. Therefore, it is essential to highlight the importance of CSA as a body size descriptor that will significantly impact upon CCTA dose.

Several literature reviews have been conducted to investigate radiation dose data from CCTA.[13,14] However, most of the studies obtained data form one CT centre, with a limited number of patients and CT scanners equipped with similar dose saving technologies. Thus, the data are not very representative of the radiation dose in current medical imaging practice. Only one recent national CCTA radiation dose survey in the United Kingdom provided a broader view of "real-world radiation dose data" and the factors associated with CT dose.[15] However, the study did not consider some factors that could impact upon dose. In particular, the work did not explore the impact of CSA of the chest and the impact of the non-enhanced calcium score (CS) test on the total dose. Establishing the associated factors for high doses and dose variations would inform optimisation strategies. Therefore, the aim of this study was to examine the associated factors for dose variation in CCTA.

## METHODS AND MATERIALS

### Data collection

The human research ethics committee (HREC) of the University of Sydney approved this study (2015/605 and 2016/742). A total of 648 CCTA data of adult patients were retrieved from 22 CT facilities across Australia (11 centres) and Saudi Arabia (11 centres) for the purpose of establishment of NDRLs for CCTA in each country. Only data for patients who underwent CCTA procedure due to coronary artery stenosis were considered in the study. A data questionnaire divided into two parts was used for the work. The first part of the questionnaire, the facility survey, fielded questions pertaining to the CT scanner equipment and the CCTA scanning parameters that were routinely used. The second part of the questionnaire was a CCTA dose survey designed to record both the individual patient and scanning parameters in addition to the CT dosimetric parameters. Data for at least 20 most current CCTA patients per site were collected retrospectively from the Radiology Information System and Picture Archiving and Communication System. Part 2 included:

- Patient parameters: age, sex, weight, height, and anteroposterior (AP) and transverse (T) diameters of chest. The CSA of the chest was calculated as shown in equation 1 below:

$$CSA\ \left(\mathrm{cm}^2\right) = \pi \times \frac{T}{2} \times \frac{AP}{2} \quad (1)[7]$$

- Scanning parameters for each exam;
- CT dose quantities [volume CT dose index ($CTDI_{vol}$) and dose–length product (DLP)] for angiographic scan (CCTA) and CS test were collected, analysed and reported separately. The radiation doses from scanogram (scout view), test boluses or bolus tracking test were not included in the analysis.

To estimate the effective dose in mSv, dose reporting software package (CT-Expo™ v. 2.4; Medizinische Hochschule, Hannover, Germany) was used. The calculation was performed in accordance with the International Commission on Radiological Protection (ICRP) Publication Number 103.[16]

### Statistical analysis

The data sets were reviewed carefully and all data sets that did not contain patient weight and CSA measurement, AP and transverse diameters, of chest were excluded. In total, complete data sets from 423 patients were provided by 17 CT centres across Australia (8 centres) and Saudi Arabia (9 centres).

All statistical analyses were performed using the Statistical Package for the Social Sciences (SPSS) software (v. 24.0, IBM Corp. Armonk, NY). A test of normality was performed using visual assessment of histograms and plots as well as skewness and kurtosis statistics. Patients' characteristics, such as weight and CSA measurement, were normally distributed in both countries. Thus, independent sample *t*-test was used to compare body size parameters between the two countries. The analysis showed no significant variation in these characteristics between two countries. The *p*-value for weight and CSA was 0.61 and 0.11 respectively. All CCTAs included in the study were performed using CT scanners recommended by the National Institute for Health and Care Excellence for cardiovascular imaging and considered as new CT imaging systems.[17] All included CT scanners had standard annual QC certificates. Thus, the data from the two countries can be treated as having similar characteristics for statistical purposes.

Although $CTDI_{vol}$ is a useful CT dose descriptor for comparing the radiation doses received from different imaging protocols, the value of the $CTDI_{vol}$ does not reflect the total absorbed dose resulted from the entire number of slices included in the CT examination. This is because $CTDI_{vol}$ depends only on the slice thickness and distance between slices (pitch).[18] Thus, DLP was used for the analysis, as it represents the integrated radiation dose from all slices included in the entire scan.[19] DLP is calculated by multiplying the $CTDI_{vol}$ by scan length.

The distribution of DLP for all patients was tested for normality using the Kolmogorov–Smirnov test and the *p*-value was 0.001 meaning the data were non-parametric. Thus, Mann–Whitney test was used to define if there were differences in DLP between CCTA scanning modes prospective and retrospective ECG-gating modes. Mann–Whitney analysis showed that the DLP for retrospective ECG-gating was significantly higher than the one for prospective ECG-gating, suggesting that using data from both

scanning modes may affect the analysis and skew the results. Therefore, data from CCTAs using prospective ECG-gating were used to analyse the impact of patient parameters on DLP, as this is the routinely used clinical scanning mode ($n$ = 323, 76%). To enable multiple regression analysis, a natural logarithm transformation was performed to normalise the DLP and the independent $t$-test was used to assess the difference between CCTAs using prospective ECG-gating with and without padding time. To evaluate whether using short padding time could reduce the radiation exposure, CCTAs performed using padding time of 275 ms ($n$ = 18), and 160 ms ($n$ = 21) were compared. All included prospective ECG-gating scans were performed using 320-slice MDCT scanners (Toshiba Medical Systems Corporation, Otawara, Japan). The scanning protocol was 320 × 0.5 mm collimation; rotation time 0.35 s and 100 kV.

To evaluate the impact of patient weight variation on DLP, the data were categorised into four groups based on the surveyed population weight distribution and taking into account the average weight recommended for establishing DRLs (70 ± 10 kg).[5] Participants were classified into four groups: below standard weight,<60 kg, ($n$ = 39), standard, 60–80 kg, ($n$ = 133), above standards,>80–100 kg, ($n$ = 110) and high weight,>100 kg, ($n$ = 41). The Shapiro–Wilk test showed that the data for each group was normally distributed ($p > 0.05$), therefore a one-way ANOVA was used to determine if the DLP value was different for groups with different weight. There were no outliers, as assessed by boxplot. In addition, a Pearson correlation analysis was performed to assess the relationship between DLP and weight and CSA. The relationship between weight and CSA for standard patients (60–80 kg) undergoing CCTA using prospective ECG-gating scan was assessed using the linear regression equation

$$y = abX \quad (2)$$

Where "$y$" represents the CSA and "$X$" is the lower and upper weight limit for the group of standard weight (60–80 kg). Lastly, a stepwise regression analysis was performed to predict the contribution of kV, padding time technique, CSA, and weight to DLP as those variables were confirmed to have strong contributors to DLP in CCTA.[7,20] Tube current (mA) was not included in the regression analysis as all CCTAs were performed using tube current modulation and was adjusted according to patient's size. It is important to know that scan length is an essential factor that must be incorporated into the analysis of variability in DLP during CT examinations of a larger area such as whole chest and abdomen. Only CCTAs with similar scan lengths were included. Examinations that required a much extended scan range such as CCTA for bypass grafts were excluded in the survey. Therefore, scan range was not included in the regression model.

## RESULTS

### Patients characteristics

Data sets from 423 patients were used, and 60% of patients included in the study were male and 40% were female, with an average age of 54 ± 14 years for both genders. The population's weight was within the standard patient size (70 ± 15 kg) commonly considered for establishing the DRLs for CT in European countries.[21] The median $CTDI_{vol}$, DLP and effective dose for the whole survey cohort were 18 mGy, 256 mGy.cm, 5.2 mSv respectively. Patient distribution and key characteristics for the sample are summarised in Table 1.

### scanning characteristics

In total, 17 CT systems from different manufacturers were surveyed: 64-slice CT General Electric (GE Healthcare, Milwaukee, WI, $n$ = 9); 128-slice Philips scanner (Philips Healthcare, Best, Netherlands, $n$ = 1); 64–128 slice, single and dual-source system Siemens scanner (Siemens Healthineers, Forchheim, Germany, $n$ = 3); 320- slice CT Toshiba systems (Toshiba Medical Systems Corporation, Otawara, Japan, $n$ = 4). The median DLP of these CT scanners ranged from 60 to 1011 mGy.cm (Figure 1). The included examinations involved 323 CCTAs (77%) performed using prospective ECG-gating and 100 (23%) of these were acquired using retrospective ECG-gating with tube current modulation. Flash protocol technology (high-pitch spiral scan using dual-source CT technology) was used in 18% of the prospective ECG-gating subgroup. Scanning with padding technique was used in 52% of CCTA studies. Padding times used in this study ranged from 60 to 250 ms. More than 70% of centres surveyed performed a CS test prior to the angiographic phase and axial scan during CS was the preferred protocol for 42% of CT centres surveyed, CS test dose is reported in Table 2.

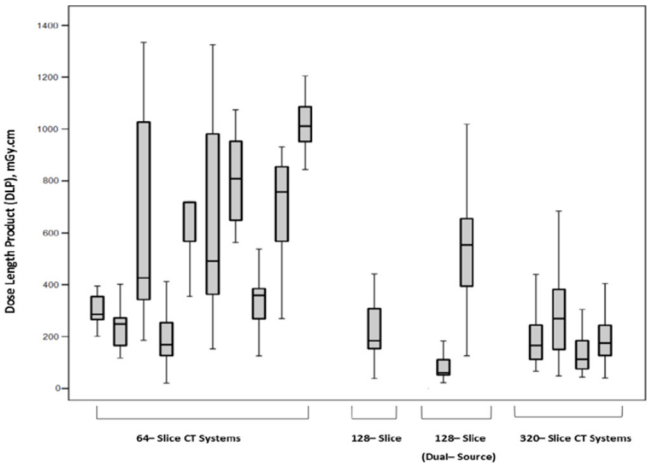
For all included CT scanners, tube voltage ranged between 80 kV and 153 kV with a mean of 112 ± 13 and median of 120 kV. A tube voltage of 120 kV or more was applied in 60% of CCTA scanning protocols ($n$ = 253 patients), and 100 kV or less was used in 170 patients (40%). Furthermore, tube current–time

Table 1. Characteristics of patients and number of CT centres surveyed

| Sample characteristics | Australia | Saudi Arabia | Total |
|---|---|---|---|
| | Number (%) | | |
| CT centres | 8 (47%) | 9 (53%) | 17 |
| Sample size | 251 (59%) | 172 (41%) | 423 |
| | Mean ± SD | | |
| Patient weight,(kg) | 81 ± 18 | 81 ± 17 | 81 ± 18 |
| Cross-sectional area ($cm^2$) | 799 ± 201 | 831 ± 194 | 812 ± 198 |

SD, standard deviation.

Figure 1. Distribution of DLP across CT centres and for different CT scanners based on number of slices: the lower and upper edges of the boxes indicate the 25th and 75th percentiles, respectively. The lines inside the boxes indicate the median and the whiskers indicate the smallest and largest values. DLP, dose–length product.




product (mAs) was adjusted to patient size during scanning, thus the mean mAs, 188 ± 85 and median of 175, varied between different CCTA protocols and scanning modes.

### Scanning technique analysis

Mann–Whitney analysis showed the distributions of DLP values for prospective and retrospective ECG-gating modes were statistically significantly different. DLP for retrospective ECG-gating was significantly higher than that for prospective ECG-gating, $U = 2147$, $p = 0.001$. The independent *t*-test showed that DLP from CCTAs with padding was significantly higher than that without the padding technique, $t\,(286.3) = -5.13$, $p = 0.001$. Analysis of variance also showed no statistically significant difference in mean DLP between two padding time groups, $t\,(37) = 0.47$, $p = 0.643$. A summary of radiation doses from different scanning technique are presented in Table 3.

### Body size analysis

Pearson's correlation analysis showed a strong positive association between weight and CSA ($r = 0.78$, $p = 0.001$), with the coefficient of determination of 60% (Figure 2). There was a moderate positive correlation between DLP with both weight and CSA ($r = 0.42$ and 0.48 respectively, $p = 0.001$). DLP values were statistically significantly different between different weight groups ($F\,(3, 115.3) = 26.76$, $p = 0.001$). DLP increased proportionately with weight: below standard weight ($M = 4.6$, SD = 0.86); standard ($M = 5.1$, SD = 0.75); above standard ($M = 5.3$, SD = 0.65); and high ($M = 5.8$, SD = 0.44). *Post hoc* analysis revealed that the mean increase in DLP between all groups was statistically significant ($p = 0.001$) except between standard and above standard groups (0.23, 95% CI: 0.005–0.46, $p = 0.057$). Patient characteristics and scan parameters of each group are displayed in Table 3.

A linear regression equation was used to describe the relationship between the weight for standard sized patient group (70 ± 10 kg) and CSA value for similar group. From previous equation, the slope value "b" representing how much CSA changes with weight is 8.52. The intercept "a" is equal to 118.29.

$$CSA = 118.298.52 \times Weight\ (60 - 80)$$

The resultant CSA range is varied from 630 to 800 $cm^2$.

Table 4 presents patient and scanning characteristics for corresponding CSA group of patients compared to standard weight group.

### Regression analysis

The stepwise regression model predicted the factors associated with DLP for prospective ECG-gating data, $F\,(3, 319) = 117$, $p < 0.001$, $R^2 = 0.524$. The variables kV, padding time technique and CSA, predicted DLP, $p < 0.05$. Patient weight was excluded from the model of regression, as it did not statistically significantly predict DLP, $p = 0.064$. The kV was the strongest contributor to DLP ($R^2 = 0.475$) and accounted for 48% of the total variation in DLP. Likewise, regression coefficients showed that kV is the more significant predictor (standardised coefficient (β) = 0.57) of DLP than padding technique and CSA, with β values of 0.18 and 0.17 respectively. The final model is shown in Table 5.

## DISCUSSION

The current study found that the median DLP and effective dose for prospective ECG-gating was significantly higher than that for prospective ECG-gating, which is consistent with previously published studies.[22] Results also confirm the increasing trend

Table 2. Value of different dose parameters by scanning technique of patients in study

| Scan technique | Dose parameters, median (interquartile range) | | |
|---|---|---|---|
| | $CTDI_{vol}$ (mGy) | DLP (mGy.cm) | Effective dose (mSv) |
| CCTA[a] ($n = 423$) | 18 (10–37) | 256 (136–518) | 5.2 (3–10) |
| RGM ($n = 100$) | 47 (41–54) | 794 (568–1003) | 15 (9–18) |
| PGM with padding ($n = 167$) | 18 (12–26) | 244 (147–359) | 5 (3–7) |
| PGM without padding ($n = 156$) | 10 (5–18) | 152 (72–274) | 3 (2–6) |
| CS test ($n = 218$) | 4.2 (3.9–5.8) | 69 (51–117) | 1.3 (1–1.7) |

CCTA, cardiac CT angiography; $CTDI_{vol}$, volume CT dose index; DLP, dose–length product.
[a]All CCTA examinations were included

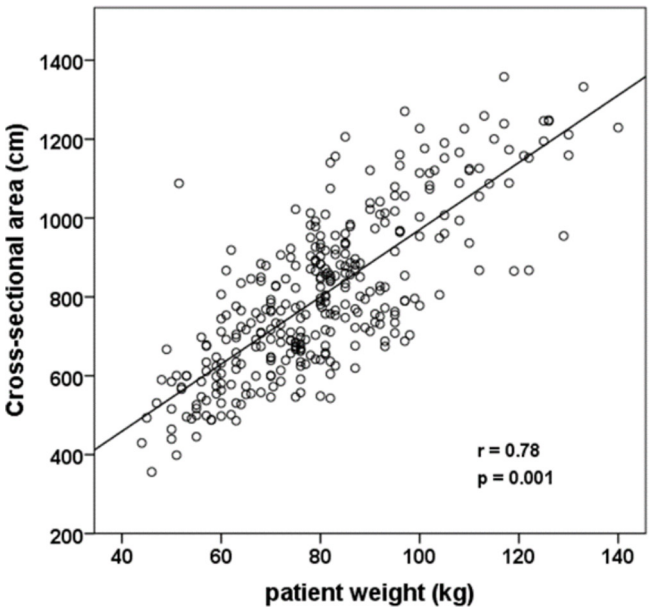
Table 3. Patient and scanning parameters of four different weight groups

| | Below standard weight <60 kg | Standard weight 60–80 kg | Above standard >80–100 kg | High weight >100 kg |
|---|---|---|---|---|
| | *No. or (Mean ± SD)* | | | |
| Sample size | 39 | 133 | 110 | 41 |
| Sex | | | | |
| Female | 26 | 62 | 43 | 8 |
| Male | 13 | 71 | 67 | 33 |
| Weight (kg) | 54 ± 4 | 71 ± 6 | 88 ± 6 | 115 ± 10 |
| BMI (kg $m^{-2}$) | 21 ± 2 | 26 ± 3 | 31 ± 4 | 38 ± 5 |
| CSA ($cm^2$) | 562 ± 117 | 731 ± 126 | 863 ± 148 | 1112 ± 131 |
| kV | 96 ± 14 | 106 ± 10 | 112 ± 11 | 121 ± 5 |
| mAs | 147 ± 74 | 190 ± 96 | 205 ± 87 | 222 ± 75 |
| **Dose parameters** | **Median (Interquartile range)** | | | |
| $CTDI_{vol}$ (mGy) | 6.5 (4–11) | 12 (7–21) | 16 (11–24) | 25 (19–37) |
| DLP (mGy.cm) | 93 (51–193.5) | 156 (95–269.5) | 221 (144–318) | 308 (241–448) |
| Effective dose (mSv) | 2.2 (1.4–4.1) | 3.5 (2–5.8) | 4.6 (2.8–6.3) | 5.9 (4–7.2) |

BMI, body mass index; CSA, cross-sectional area; $CTDI_{vol}$, volume CT dose index; DLP, dose–length product; SD, standard deviation.

towards employing prospective ECG-gating technique as a sole CCTA imaging method to minimising radiation dose without compromising image quality. With the introduction of flash dual-source CT, prospective ECG-gating can successfully scan patients with high and irregular heart rates.[23] Thus, this technique can be employed as a routine CCTA imaging technique rather than retrospective spiral scan. Stepwise regression analysis from prospective ECG-gating examinations showed that tube voltage was the most significant determinant of dose, (β = 0. 57)

Figure 2. Linear regression plot between CSA of chest and patient weight. A significant correlation was noted ($r$ = 0.78, $p$ = 0.001). CSA, cross-sectional area.




followed by the application of padding time technique and CSA of chest. Although high kV (>120 kV) is preferable to improve image quality for heavy and large patients,[24] tube voltage higher than 120 kV was only used in 11% of CCTAs for very obese patients in the current work. This is an interesting finding that may be worth further consideration. However, it is crucial that the care should be taken when reducing kV as image quality could be affected because of more scattered radiation and beam hardening may occur. This is mainly an issue in a patient with high-risk patients who may need multiple CT imaging. Therefore, dose optimisation through kV control should be applied with caution.

Scanning large patients during CCTA is challenging because it requires a higher kV and mAs to increase photon absorption through adipose tissues. This can result in a higher radiation dose. We found that the effective dose for the very obese patient group was 69% higher than that for the standard weight patient group (60–80 kg), and significantly higher than for other patient groups (above standards, >80–100 kg and high weight, >100 kg). Although effective dose was lower than reported in previous CCTA studies utilising standard average weight,[25,26] the finding emphasises the need to report dose quantities from different patient weight groups. Further work should investigate the utility of DRLs for patients outside the standard 60–80 kg category.

The wide variability in DLP between centres using a similar CT technology (Figure 1) suggests that factors other than technology significantly contribute to dose variations. This was particularly evident in 128-slice dual source scanners. It is logical that since the routine CT scanning protocol is usually fixed in a given CT centre, the variation in scanning protocols including exposure factor selection and scan length across centres as well as

Table 4.Patient and scanning characteristics for corresponding CSA group and standard weight group

| | Standard CSA 630–800 $cm^2$ | Standard weight 60–80 kg |
|---|---|---|
| | *No. or (Mean ± SD)* | |
| Sample size | 113 | 133 |
| Sex | | |
| Female | 47 | 62 |
| Male | 66 | 71 |
| BMI ($kg/m^2$) | 27 ± 4 | 26 ± 3 |
| kV | 107 ± 10 | 106 ± 10 |
| mAs | 193 ± 94 | 190 ± 96 |
| **Dose parameters** | *Median (Interquartile range)* | |
| $CTDI_{vol}$ (mGy) | 13 (6–18) | 12 (7–21) |
| DLP (mGy.cm) | 186 (80–251) | 156 (96–269) |
| Effective dose (mSv) | 3.6 (1.9–5.9) | 3.5 (2–5.8) |

BMI, body mass index; CSA, cross-sectional area; $CTDI_{vol}$, volume CT dose index; DLP, dose–length product.

differences in patient physical characteristics may be responsible for the wide dose variations noted between the centres using a similar technology.[11] However, results show that the scan length for CCTA is short and generally consistent across the centres surveyed (mean 15 ± 2 cm). Thus, scan length may have had the minor influence on DLP in the current work.

Dose-reduction strategies and dose surveys in CT are normally based on the use of one patient size characteristic, usually the patient's weight.[27] For instance, the latest ICRP guidelines for setting DRLs require the inclusion of a group of standard-sized patients within 70 ± 10 kg to compare the result with other international DRLs values. If the patient weight was not routinely recorded, then data from a larger group of patients are required to reduce the contribution of weight for an individual on the median dose.[5] However, patient weight is not often measured or recorded at the time of CCTA examination; this can reduce the available data and extend the period needed for data collection. During the data collection period, participating radiographers spent a long time collecting weight and height information from patients' electronic records, as these parameters are not included in Picture Archiving and Communication System. Also, a previous NDRLs study in Australia showed a substantial variation in $CTDI_{vol}$ and DLP in CT centres that did not apply weight restriction criteria, which was attributed to a wide patient-size range scanned in the same centre. Therefore, the current study explored CSA as an alternative to weight for reference dose recommendation and adaptation of scanning parameters, dose reduction strategies, and the establishment of CCTA DRLs. The current work shows a strong positive correlation between weight and CSA, with CSA of chest increasing as the weight of the patient increases, ($r = 0.78$, $p < 0.001$). Although both variables had moderate positive correlation with DLP, CSA had a stronger correlation than weight ($r = 0.48$ and 0.42 respectively, $p < 0.001$). However, regression analysis show that CSA was a stronger predictor of DLP whilst patient weight had no effect on radiation dose. This finding is reasonable given that the automodulation function in current scanners automatically tailor the exposure factors to patient dimensions.

Table 5. Contribution of patient and technical parameters to DLP for prospective mode

| Predictor | β | *t* score | *p* value |
|---|---|---|---|
| Tube voltage (kV) | 0.569 | 12.277 | 0.001 |
| Padding time[a] | 0.178 | 4.529 | 0.001 |
| Cross-sectional area ($cm^2$) | 0.171 | 3.742 | 0.001 |
| Patient weight (kg)[b] | 0.055 | 1.141 | 0.064 |

DLP, dose–length product.
[a]Coded 0 = no padding time technique, 1 = padding time technique.
[b]excluded variable.

The CSA values in this study looks comparable with other published studies on CSA of chest. The 2011 DRL study in UK[7] found a mean CSA = 712±195 $cm^2$ and the American CCTA study[28] found a CSA of 792 ± 177 $cm^2$. In addition, the standard weight (70 ± 10 kg) and corresponding standard CSA values (630–800 $cm^2$) were frequently concordant (Figure 2). The scanning parameters and dose descriptors between those groups were statistically similar ($p > 0.05$). Therefore, CSA could be considered as an alternative measure of patient size to weight for setting CCTA DRLs and dose optimisation strategies for most chest CT examinations. These measurements can be easily obtained using the digital calipers on the CT display console form axial or scanogram images. Tmeasurement usually take 30–40 s. This can be done by researchers retrospectively where the patient weight data are not available. However, reconstruction of the small field of view (FOV) over the cardiac region to a wider field of viewV should be obtained first if the AP and transverse diameters calculated from an axial scan. Automatic tube current modulation has been shown to lower dose without compromising image quality.[29] Therefore, the ability of current CT systems to automatically modulate exposure parameters according to patient

dimensions favors the use of CSA for establishing DRLs for CCTA. However, further work is needed to establish whether CSA vary by weight and if these differences are consistent with dose and image quality.

The padding time technique is important for improving diagnostic accuracy by increasing the scanning time prior to, and after the selected phase of the cardiac cycle, thereby increasing the window for reconstruction.[30] While radiation doses from prospective ECG-gating scans with padding were significantly lower than those from retrospective ECG-gating, the current study confirms the critical role of padding time in dose optimisation during prospective ECG-gating scan, however this technique should be used with caution. For example, no padding time should be used in CCTA examinations of patients with well-controlled heart rate. On the other hand, using short padding time in a patient with irregular heart rhythm or with very high heart rate may result in lower diagnostic image quality. However, the 320-slice scanners included in the current survey have wide detector array and always require some padding time as a full tube rotation is required to correct for the wide cone beam without increasing the dose. Therefore, no padding time is only feasible in detectors with <4 cm *z*-axis.

The analysis demonstrated that radiation dose increased with the use of padding time and the median DLP was significantly increased by 61%. A noticeable variation in the routine padding time used during CCTA was also noted, with results showing that prospective ECG-gating with 275 and 160 min padding time increasing the DLP by 39 and 23%, respectively, compared to prospective ECG-gating using no padding time. Although the differences in median DLP between previous padding times were not significant, further reduction of the time appeared to be more practical in dose saving during CCTA. This is consistent with studies, which reported a further decrease in CCTAs doses with low padding time (50–80 ms) without impairing diagnostic accuracy.[31,32]

The calcium score (CS) test is routinely employed in more than 70% of the centres surveyed. It is recommended that dose from CS test should average between 0.5 and 1.5 mSv on a new CT scanner.[33] The current study show that the dose from CS remained widely variable and 33% of included CS tests had above 1.5 mSv with one CT centre having a median effective dose of 4 mSv. Additionally, dose from CS testing accounted for 15% of the overall radiation burden for CCTAs. These findings of increasing CS dose from current study emphasise that CT centres performing CS test should employ strategies to minimize radiation dose such as axial scanning mode without affecting the diagnostic image quality.[34] This dose saving technology significantly lowers the dose compared to a routine helical scan. The median DLPs for axial and helical scans were 56 and 69 mGy. cm, respectively, $p = 0.001$. These findings imply that doses from CS test are not as low as assumed, and dose reduction strategies should take the CS test into consideration. Overall, our findings show that dose saving during CCTA is achievable through technology and proper tailoring of CCTA protocols according to patient characteristics. The clinical translation of these findings through educational and training programs for CT radiographers may facilitate improved optimisation strategies and reduce high doses and dose variations from CCTA.

Although the work identified the major contributors to dose variation, several limitations need to be acknowledged. First, although the application of iterative reconstruction algorithms can reduce the effective dose significantly,[30] the effect of using different types and levels of iterative reconstruction algorithms on radiation dose were not evaluated in this work. Secondly, the questionnaire used in the survey did not include patient heart rate, which plays a role in optimising radiation doses during CCTA. Further work is needed to assess the effect of using variable padding times on patients with different heart rate and its relative influence on radiation dose. Also, size-specific dose estimates may more accurately represent the actual dose received by the patients undergoing CCTA than effective dose, as it allows estimation of dose based on $CTDI_{vol}$ and patient size.[35]

## CONCLUSION

Radiation dose variation appears to be influenced by several associated factors in CCTA and they are in order of influence: employing prospective ECG-gating protocol, kV, using padding time technique and CSA of the chest. The results showed that using prospective ECG-gating is the main technique aid to a significant dose reduction and that padding time also increased DLP by 61% compared to prospective ECG-gating with no padding. Tube voltage accounted for 48% of the total variation in DLP. Results emphasise the need to include CSA measurements in future CCTA dose surveys and for proposing CCTA NDRLs. The findings should inform educational and training interventions to optimise their CCTA protocols.

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