Estimated Radiation Dose Associated With Cardiac CT Angiography

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Context Cardiac computed tomography (CT) angiography (CCTA) has emerged as a useful diagnostic imaging modality for the assessment of coronary artery disease. However, the potential risks due to exposure to ionizing radiation associated with CCTA have raised concerns.

Objectives To estimate the radiation dose of CCTA in routine clinical practice as well as the association of currently available strategies with dose reduction and to identify the independent factors contributing to radiation dose.

Design, Setting, and Patients A cross-sectional, international, multicenter, observational study (50 study sites: 21 university hospitals and 29 community hospitals) of estimated radiation dose in 1965 patients undergoing CCTA between February and December 2007. Linear regression analysis was used to identify independent predictors associated with dose.

Main Outcome Measure Dose-length product (DLP) of CCTA.

Results The median DLP of 1965 CCTA examinations performed at 50 study sites was 885 mGy · cm (interquartile range, 568-1259 mGy · cm), which corresponds to an estimated radiation dose of 12 mSv (or 1.2 × the dose of an abdominal CT study or 600 chest x-rays). A high variability in DLP was observed between study sites (range of median DLPs per site, 331-2146 mGy · cm). Independent factors associated with radiation dose were patient weight (relative effect on DLP, 5%; 95% confidence interval [CI], 4%-6%), absence of stable sinus rhythm (10%; 95% CI, 2%-19%), scan length (5%; 95% CI, 4%-6%), electrocardiographically controlled tube current modulation (−25%; 95% CI, −23% to −28%; applied in 73% of patients), 100-kV tube voltage (−46%; 95% CI, −42 to −51%; applied in 5% of patients), sequential scanning (−78%; 95% CI, −77% to −79%; applied in 6% of patients), experience in cardiac CT (−1%; 95% CI, −1% to 0%), number of CCTAs per month (0%; 95% CI, 0%-1%), and type of 64-slice CT system (for highest vs lowest dose system, 97%; 95% CI, 88%-106%). Algorithms for dose reduction were not associated with deteriorated diagnostic image quality in this observational study.

Conclusions Median doses of CCTA differ significantly between study sites and CT systems. Effective strategies to reduce radiation dose are available but some strategies are not frequently used. The comparable diagnostic image quality may support an increased use of dose-saving strategies in adequately selected patients.

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egies with dose reduction, and (4) the independent factors contributing to radiation dose.

METHODS
Study Protocol
The Prospective Multicenter Study On Radiation Dose Estimates Of Cardiac CT Angiography In Daily Practice I (PROTECTION I) is an international, investigator-driven, industry-independent, observational study. Physicians performing CCTA at 120 different CCTA sites worldwide were invited to participate on the basis of previous publications on CCTA and personal contacts. We intended to include a minimum of 20 study sites that would enroll approximately 20 patients during 1 month in this trial. Therefore, we expected at least 400 CCTAs for data analysis. The participating physicians were asked to enroll all consecutive patients undergoing electrocardiographically triggered or electrocardiographically gated CCTAs during the duration of 1 month between February and December 2007. The indications for CCTA comprised (1) the assessment of the coronary arteries or bypass grafts, (2) chest pain protocols for the combined visualization of the coronary and pulmonary arteries as well as of the thoracic aorta, and (3) visualization of cardiac anatomy before or following electrophysiologic procedures. Image data as well as CCTA study details were collected and analyzed in a central CCTA core laboratory. Experience in CCTA was defined by the period for which each study site had been performing and reading cardiac CT studies as well as the number of CCTAs that were performed during the month of enrollment. Typical-sized patients were defined by a body mass index (BMI, calculated as weight in kilograms divided by height in meters squared) of 20 to 30. Stable sinus rhythm was defined by the presence of sinus rhythm without arrhythmias or premature beats during CT preparation and the scanning procedure. The study was approved by the ethics committee, and all patients gave written informed consent as required at the individual study sites.

Estimation of Radiation Dose
The participating physicians obtained the parameters relevant to radiation dose from the scan protocol generated by the CT system after each CCTA study. The parameters included the volume CT dose index (CTDIvol) and DLP. The CTDI value, which is a basic radiation dose parameter of CT, can be measured and calculated as a mathematical integral under the radiation dose profile of a single rotation scan that would produce one tomographic image at a fixed table position. The CTDIvol represents the average radiation dose over a specific investigated volume. The DLP, which equals the CTDIvol multiplied by the respective scan length, mirrors best the radiation a patient is exposed to by the entire CT scan. This parameter was used as the primary outcome measure in our study.

The effective dose of CCTA can be estimated by a method proposed by the European Working Group for Guidelines on Quality Criteria in CT. This method has been shown to be reasonably robust and consistent for estimating the effective dose. The effective dose is derived from the product of the DLP and an organ weighting factor for the chest as the investigated anatomic region. This organ weighting factor \( k = 0.014 \frac{mSv}{(mgY \times cm)^{-1}} \) is averaged between male and female models.

Strategies for Reduction of Radiation Dose
Automated Exposure Control. This dose-saving algorithm, also referred to as anatomy-based adaptation of the tube current, automatically adjusts the tube current according to the patient’s size, anatomic shape, or both (eg, the tube current is increased for obese patients and decreased for small patients to maintain an optimal image quality at the lowest dose). Although additional algorithms are available to modulate the tube current online during noncardiac scanning, the adapted tube current usually remains constant for the entire scan range in the cardiac automated exposure control mode.

Electrocardiographically Controlled Tube Current Modulation. Electrocardiographically controlled tube current modulation (ECTCM) has been shown to effectively reduce radiation dose during retrospective electrocardiographically gated cardiac spiral CT. Because cardiac motion is greatest during systole and least during diastole, diastolic image reconstructions are most likely to provide motion-free data sets. Accordingly, this algorithm restricts the prescribed tube current to a predefined time window during the diastolic phase and decreases tube current in the systolic phase of the cardiac cycle. Because the algorithm increases or decreases tube current prospectively, a regular heart rhythm is required to avoid applying the wrong tube current to the cardiac phase of interest.

Tube Voltage. Usually, CCTA is performed using a tube voltage of 120 kV. However, CCTA acquisition with 100-kV tube voltage is also possible and has been suggested as a means to lower radiation dose. Reducing tube voltage is a standard procedure in pediatric CT and it has been used in cardiac CT primarily in nonobese patients (body weight \( \leq 85 \text{ kg or BMI} \leq 30 \)) owing to increased image noise. In addition to increasing image noise, a lower tube voltage also increases contrast in scans performed with the use of iodinated contrast agents, because iodine absorption is higher at lower tube voltage settings.

Sequential Scanning. The prospective electrocardiographically triggered sequential scan mode has recently been reintroduced into CCTA. Compared with the conventional retrospective electrocardiographically gated spiral scan technique, which applies radiation during the entire cardiac cycle, radiation is only administered at one predefined time window of the cardiac cycle within the sequential scan mode. The radiation tube is inactive during the remainder of the cardiac cycle, which leads to substantial reductions in dose. However, this scan mode allows minimal or no flexibility in retrospectively choosing different phases of the cardiac cycle for image reconstruction once the data have been acquired.
of randomly selected CCTAs performed for the assessment of the coronary arteries.

**Statistical Analysis**

Results are expressed as counts (or proportions in %) or as median (interquartile range [IQR]). Continuous and categorical variables were analyzed with a Wilcoxon rank sum and \( \chi^2 \) test as appropriate. A multivariable linear regression model was used to identify patient and imaging characteristics simultaneously predictive of radiation dose. To avoid overfitting the model of the multivariable model, we entered only variables with \( P < .10 \) in the univariate analysis. In addition, bootstrapping with 2000 replications and grouping for study sites was applied for the calculation of regression coefficients and 95% confidence intervals (CIs) for each covariate in the model, as well as for model calibration and validation.\(^6\) Due to the lack of normal distribution of DLP, we used the logarithm of DLP to approximate normal distribution of DLP, we used the generalized estimation equation model.\(^{14} \) The R Project for Statistical Computing was used for statistical analysis.\(^{15} \) Statistical significance was defined as \( P < .05 \).

**RESULTS**

Investigators from 50 international study sites (21 university hospitals and 29 community hospitals) agreed to participate in the study; no investigator or study site was excluded. These CCTA sites contributed 1965 patients undergoing cardiac CT angiography in daily practice (median, 31 patients per site during the month of enrollment; IQR, 19-48). The median prior study site experience in the acquisition and interpretation of cardiac CT scans was 35 months (IQR, 18-57 months). Patient and CCTA study characteristics are shown in Table 1. Visualization of the coronary arteries was the main indication for CCTA (82% of patients), whereas visualization of bypass grafts, planning CTS for electrophysiologic procedures, or the evaluation in patients with acute chest pain were infrequent indications, representing the remaining 18% of the enrolled patient examinations. Sinus rhythm was present in 1874 patients (95%), \( \beta \)-Blockers were administered in 904 patients (46%), resulting in a median heart rate of 61/min (IQR, 55-75/min) during scanning. With a median scan length of 137 mm (IQR, 120-156 mm) and a median CTDI\(_{vol}\) of 52.7 mGy (IQR, 37.1-72.8 mGy), the median DLP was 885 mGy/cm (IQR, 508-1259 mGy/cm) (Figure 1). This corresponds with an estimated effective radiation dose of 12 mSv (IQR, 8-18 mSv). The median DLP per site differed substantially between the study sites (Figure 2). Median DLPs per site ranged from a minimum of 331 mGy/cm to a maximum of 2146 mGy/cm, which corresponds with a range of median estimated effective radiation dose from 5 mSv to 30 mSv.

A small number of patients (72 [4%]) were studied with the use of 16-slice CT systems, while the majority of patients (1893 [96%]) were studied using 64-slice CT systems. Due to this imbalance, the subsequent analyses were limited to 47 study sites with 64-slice CT systems (1893 patients). Table 2 shows the patient and CT scan characteristics of patients undergoing coronary CT angiography according to the used 64-slice CT system.

A total of 1197 of 1546 patients (77%) undergoing 64-slice CCTA for the visualization of the coronary arteries had a BMI of 20 to 30. In this typical-sized patient population, the median CTDI\(_{vol}\) and DLP were 50.4 mGy (IQR, 36.1-69.6 mGy) and 827 mGy/cm (IQR, 546-1152 mGy/cm), respectively.

**Independent Predictors for Radiation Dose**

In the univariate analysis, 11 of 14 variables demonstrated a significant association with DLP and were entered into the multivariable linear regression analysis (Table 3). In the multivariable linear regression analysis, increasing patient weight and the absence of a stable sinus rhythm were independently associated with a higher DLP (Table 3), whereas the indication for CCTA demonstrated no independent association. A 1-cm increase in the scan length was associated with a 5% increase in DLP (95% CI, 4%-6%). Among patients, the median prior study site experience in the acquisition and interpretation of cardiac CT scans was 35 months (IQR, 18-57 months). Patient and CCTA study characteristics are shown in Table 1. Visualization of the coronary arteries was the main indication for CCTA (82% of patients), whereas visualization of bypass grafts, planning CTS for electrophysiologic procedures, or the evaluation in patients with acute chest pain were infrequent indications, representing the remaining 18% of the enrolled patient examinations. Sinus rhythm was present in 1874 patients (95%), \( \beta \)-Blockers were administered in 904 patients (46%), resulting in a median heart rate of 61/min (IQR, 55-75/min) during scanning. With a median scan length of 137 mm (IQR, 120-156 mm) and a median CTDI\(_{vol}\) of 52.7 mGy (IQR, 37.1-72.8 mGy), the median DLP was 885 mGy/cm (IQR, 508-1259 mGy/cm) (Figure 1). This corresponds with an estimated effective radiation dose of 12 mSv (IQR, 8-18 mSv). The median DLP per site differed substantially between the study sites (Figure 2). Median DLPs per site ranged from a minimum of 331 mGy/cm to a maximum of 2146 mGy/cm, which corresponds with a range of median estimated effective radiation dose from 5 mSv to 30 mSv.

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the dose-saving algorithms, the use of automated exposure control was not significantly associated with dose, and the use of ECTCM resulted in a reduction of DLP of −25% (95% CI, −23% to −28%). The 100-kV tube voltage or a sequential scan algorithm resulted in a reduction of DLP of −46% (95% CI, −42% to −51%) and −78% (95% CI, −77% to −79%), respectively (Table 3). A 12-month increase in experience in CCTA was also associated with a small reduction in DLP with an adjusted effect of −1% (95% CI, −1% to 0%). Finally, a significant independent effect on DLP was observed for the different 64-slice CT systems. Using the Siemens single-source 64-slice system with the lowest DLP as a reference, an independent association with a higher DLP was observed for the other four 64-slice CT systems.

**Use of Dose-Saving Algorithms and Image Quality**

Diagnostic image quality was assessed for 2092 coronary arteries (523/1546 patients [33.8%] who underwent 64-slice CCTA with the indication for the visualization and assessment of the coronary arteries).

Automated exposure control was applied in 580 patients (38%). However, the use of this dose-saving strategy was not associated with a reduction in DLP in the univariate linear regression analysis (P = .12). Diagnostic image quality was found for 97.7% and 95.6% of all coronary arteries studied without and with automated exposure control, respectively (P = .06).

In contrast, the ECTCM was applied in 1133 patients (73%) who underwent spiral data acquisition. Diagnostic image quality did not differ between patients studied with vs without ECTCM dose pulsing (97.1% coronary arteries with vs 93.7% coronary arteries without, P = .07).

A reduced tube voltage of 100 kV was applied in only 82 patients (5%), and a tube voltage of 120 kV or more than 120 kV was used in 1435 patients (93%) and 29 patients (2%), respectively. Although DLP was significantly associated with the lowered tube voltage of 100 kV, the percentage of diagnostic coronary arteries visualized with a diagnostic image quality was significantly higher in patients scanned with a tube voltage of 100 kV (96.3% coronary arteries scanned with tube voltage of ≥120 kV vs 100% coronary arteries scanned with tube voltage of 100 kV, P < .001).
### Table 2. Patient and CT Scan Characteristics for 64-Slice Coronary CT Angiography

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>GE 64 (n = 304)</th>
<th>Philips 64 (n = 123)</th>
<th>Siemens 64 Single-Source (n = 380)</th>
<th>Siemens 64 Dual-Source (n = 521)</th>
<th>Toshiba 64 (n = 138)</th>
<th>P Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body mass index&lt;sup&gt;b&lt;/sup&gt;</td>
<td>25.9 (23.2-29.4)</td>
<td>27.5 (25.4-29.7)</td>
<td>25.8 (23.4-28.4)</td>
<td>26.3 (24.1-28.7)</td>
<td>26.0 (24.3-29.4)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Without β-blockers</td>
<td>144 (37.5)</td>
<td>39 (31.7)</td>
<td>78 (20.5)</td>
<td>350 (67.2)</td>
<td>27 (19.6)</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Heart rate, beats/min</td>
<td>60 (54-67)</td>
<td>60 (54-66)</td>
<td>60 (55-65)</td>
<td>64 (56-72)</td>
<td>60 (53-65)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Automated exposure control With</td>
<td>124 (32.3)</td>
<td>68 (55.3)</td>
<td>81 (21.3)</td>
<td>236 (45.3)</td>
<td>71 (51.4)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Without</td>
<td>260 (67.7)</td>
<td>55 (44.7)</td>
<td>299 (78.7)</td>
<td>285 (54.7)</td>
<td>67 (48.6)</td>
<td></td>
</tr>
<tr>
<td>ECTCM in spiral scan With</td>
<td>248 (64.6)</td>
<td>90 (73.2)</td>
<td>228 (60.0)</td>
<td>510 (97.9)</td>
<td>57 (41.3)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Without</td>
<td>49 (35.4)</td>
<td>22 (26.8)</td>
<td>152 (40.0)</td>
<td>10 (2.1)</td>
<td>81 (58.7)</td>
<td></td>
</tr>
<tr>
<td>Tube voltage, kV</td>
<td>100</td>
<td>12 (3.1)</td>
<td>0</td>
<td>0</td>
<td>70 (13.4)</td>
<td>0</td>
</tr>
<tr>
<td>≥120</td>
<td>372 (96.9)</td>
<td>123 (100)</td>
<td>380 (100)</td>
<td>451 (86.6)</td>
<td>138 (100)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Scanning technique</td>
<td>Spiral</td>
<td>297 (77.3)</td>
<td>112 (91.1)</td>
<td>380 (100)</td>
<td>520 (99.8)</td>
<td>138 (100)</td>
</tr>
<tr>
<td>Sequential</td>
<td>87 (22.7)</td>
<td>11 (8.9)</td>
<td>0</td>
<td>1 (0.2)</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>Scan length, mm</td>
<td>139 (130-159)</td>
<td>135 (124-146)</td>
<td>123 (113-139)</td>
<td>133 (121-146)</td>
<td>120 (108-129)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>CTDIvol, mGy</td>
<td>77.3 (61.3-89.6)</td>
<td>47.0 (42.0-52.9)</td>
<td>39.6 (35.5-65.8)</td>
<td>47.8 (35.8-60.8)</td>
<td>88.0 (60.3-121.1)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Dose-length product, mGy × cm</td>
<td>1369 (814-1644)</td>
<td>707 (635-913)</td>
<td>622 (522-1023)</td>
<td>798 (580-1007)</td>
<td>1039 (808-1291)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Effective dose estimate, mSv</td>
<td>19 (11-23)</td>
<td>10 (7-13)</td>
<td>9 (7-14)</td>
<td>11 (8-14)</td>
<td>15 (11-18)</td>
<td>&lt;.001</td>
</tr>
</tbody>
</table>

**Abbreviations:** CT, computed tomography; CTDIvol, volume CT dose index; ECTCM, electrocardiographically controlled tube current modulation.

<sup>a</sup> According to used 64-slice CT system.

<sup>b</sup> Body mass index calculated as weight in kilograms divided by height in meters squared.

### Table 3. Predictors for Estimated Radiation Dose in the Univariate and Multivariable Linear Regression Analyses<sup>4</sup>

<table>
<thead>
<tr>
<th>Predictors</th>
<th>Univariate Linear Regression Analysis</th>
<th>Multivariable Linear Regression Analysis</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Effects (95% CI)</td>
<td>P Value</td>
<td>% Effects (95% CI)</td>
</tr>
<tr>
<td>Patient height, 1-cm increase</td>
<td>1 (-2 to 5)</td>
<td>.53</td>
</tr>
<tr>
<td>Patient weight, 10-kg increase</td>
<td>5 (2 to 7)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Indication, noncoronary vs coronary</td>
<td>25 (19 to 31)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Heart rhythm, nonsinus vs sinus</td>
<td>30 (22 to 43)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Heart rate, 10-beats/min increase</td>
<td>5 (3 to 7)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>β-Blocker administration for CCTA</td>
<td>-4 (-11 to 2)</td>
<td>.21</td>
</tr>
<tr>
<td>Scan length, 1-cm increase</td>
<td>6 (5 to 6)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Automated exposure control</td>
<td>-4 (-10 to 1)</td>
<td>.09</td>
</tr>
<tr>
<td>Electrocardiographically controlled</td>
<td>-19 (-25 to 13)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>tube current modulation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tube voltage, 100 kV vs ≥120 kV</td>
<td>-69 (-59 to -79)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Sequential vs spiral scanning</td>
<td>-108 (-99 to -117)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Site experience in CCTA, 12-mo increase</td>
<td>-2 (-1 to -3)</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>Performed CCTAs per mo, 10-CCTA increase</td>
<td>1 (0 to 2)</td>
<td>&lt;.001</td>
</tr>
</tbody>
</table>

**Abbreviations:** CI, confidence interval; CT, computed tomography; CCTA, cardiac CT angiography; DLP, dose-length product; NA, not applicable.

<sup>4</sup>Predictors for radiation dose are presented as % change DLP (mGy × cm).

Spiral data acquisition with retrospective electrocardiographic gating was applied in the majority of patients (1447 [94%]), whereas a sequential scanning technique with prospective electrocardiographic triggering was applied in only 99 patients (6%). The use of sequential scanning had no association with image quality. Diagnostic image quality was found for 96.6% and 98.2% of all coronary arteries with spiral and sequential scanning, respectively (P =.15). However, the mean heart rate of patients in whom sequential scanning was used was significantly lower than for patients in whom spiral data acquisition was performed (57/min [IQR, 52-61/min] for sequential scanning vs 62/min [IQR, 56-70/min] for spiral data acquisition, P = .001).

**COMMENT**

Computed tomography represents an important source of ionizing radiation arising from medical exposures. A basic principle of radiation protection is to keep radiation exposure “as low as reasonably achievable” (ALARA principle).

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However, the magnitude of radiation dose attributable to CCTA in daily practice is poorly investigated. Although several studies have shown that the radiation dose of CCTA can be reduced effectively with the use of dose-saving algorithms, it is currently unknown how often they are being used in daily practice, how effectively they reduce radiation dose, and how they influence image quality. Small series of patients undergoing CCTA have reported radiation doses of up to 21.4 mSv without use of ECTCM techniques, whereas other small series of patients reported radiation doses as low as 2.1 mSv with the application of newly available sequential scanning algorithms. Thus, the identification of factors that may influence radiation dose of CCTA may be of particular interest, because it may assist in the improvement of existing or the development of new scanning strategies to effectively reduce radiation dose.

Our multicenter study with a large unselected group of patients revealed a median DLP of 885 mGy × cm, which corresponds with an estimated effective radiation dose of 12 mSv, applying the conversion factor of 0.014 mSv × (mGy × cm)^{-1} for dose estimation. This result needs to be compared with typical effective doses of 10 mSv for an abdominal/pelvic CT scan, of 5 mSv for invasive coronary angiography, and of 11 mSv and 22 mSv for technetium-99m and thallium-201 myocardial stress nuclear scans, respectively. We observed a large site-specific variability in the DLP of CCTA in our study. The median DLP per site ranged from 331 mGy × cm to 2146 mGy × cm. This 6-fold difference in DLP illustrates the large variability in CCTA protocols, differences in the CT system characteristics, and in the use of dose-reduction algorithms between individual study sites. A variety of factors appear to contribute to this finding. Linear regression analysis identified 9 independent variables associated with DLP. The 2 patient-dependent variables of body weight and absence of a sinus rhythm, which are not modifiable, had a small to moderate effect on the DLP. In contrast, 4 factors that can be modified during the CT data acquisition have a leading association with the DLP of CCTA: (1) scan length, (2) ECTCM, (3) 100-kV tube voltage, and (4) the sequential scan mode. An increase in the scan length of 1 cm was associated with an increase of the DLP of approximately 5%. Instead of rigidly scanning from the carina to diaphragm, the CT technician might consider to individually adjust the scan range according to the given anatomy, to a prior performed low-dose scan for calcium scoring, or both. If no calcium scoring scan is performed, it may be reasonable to set the upper scan limit in the mid-pulmonary artery. If possible, long scan ranges including both the heart and the thoracic aorta should be avoided unless specifically indicated.

The use of the ECTCM was associated with a reduced DLP by 25% in our study. This observed relative reduction is lower than previously reported (37% to 48% dose reduction on one manufacturer’s system) and may be attributable to different implementations of the tube current modulation algorithm with different CT systems. In addition, some algorithms for tube current modulation are programmable by the CT technician, which may introduce an additional variation in efficacy of the dose-saving algorithm. Finally, the frequency of use of ECTCM algorithm, although applied in 73% of the entire patient population undergoing spiral data acquisition, varied widely from 41% to 98% between the different 64-slice CT systems. These results imply that further improvements of the efficacy and the usability of the ECTCM algorithms for the different CT systems is desirable, so that this strategy for dose reduction would be applied in the majority of patients.

In linear regression analysis, the use of 100-kV tube voltage, an established method for dose reduction in pediatric CT without affecting diagnostic image quality, was associated with a considerable reduction in radiation dose, because radiation dose changes approximately with the square of the tube voltage. In comparison with the standard setting of 120 kV, 100-kV tube voltage reduced the DLP by 46%. Although the analysis of diagnostic image quality suggest an improved image quality for the 100-kV data acquisition, this analysis is limited by a potential selection bias and by the nonrandomized design of our dose survey study. However, until such randomized data become available, the results of our study suggest that a 100-kV tube voltage might be considered as a promising method for CCTA dose reduction in selected patients. The application of 100-kV tube voltage has been proposed for non–overweight patients (eg, body weight ≤85 kg or BMI ≤30), because image noise increases with reduced tube voltage. Unfortunately, 100-kV tube voltage was applied in only 5% of the PROTECTION 1 population, but its potential for dose reduction becomes evident when realizing that this approach would have been possible in an additional 66% of the PROTECTION 1 population (applying a body weight of 85 kg as a threshold).

The sequential scan mode has recently been introduced into cardiac CT imaging as an alternative to the conventional spiral acquisition mode. Recent studies have shown that radiation dose of CCTA can be as low as 2.1 mSv with this sequential scan protocol in patients with a slow and regular heart rate. Within the PROTECTION 1 study, the sequential scan protocol reduced the DLP by 78% when compared with spiral scan protocols. However, this effective approach for dose reduction was used in only 6% of the patient population, which can be largely explained by the fact that most CT systems had not been upgraded to allow this scan protocol during the study period. However, had such a scan protocol been available in all CT systems, an additional 51% of patients with a stable sinus rhythm and a heart rate of 63/min or less (a threshold suggested by Hussmann et al) would have qualified to be scanned with this low-dose protocol. Similarly to the 100-kV scan protocol, the use of the sequential scan protocol was not associated with a deteriorated diagnostic image quality. However, the
limitation needs to be acknowledged that patient selection for sequential scanning was highly selective and not randomized in this study. In addition, the binary assessment of diagnostic image quality might mask smaller differences between spiral and sequential scan protocols and additional validation studies are needed to establish the diagnostic noninferiority of sequential scanning. Nevertheless, the current results are in line with previous publications that support the use of sequential scanning in selected patients.

Lowering the heart rate by β-blocker administration, which is well tolerated by patients, not only reduces motion artifacts and contour blurring but also stabilizes sinus rhythm enabling a consistent use of electrocardiographically dependent dose reduction algorithm. In addition, the efficacy of ECTCM is highly dependent on heart rate, with a higher efficacy in dose reduction at lower heart rates. Although heart rate during CCTA data acquisition and the administration of β-blockers were not associated with radiation dose in the multivariable analysis, we still encourage the consequent use of β-blockers.

Finally, linear regression analysis identified the type of 64-slice system, the experience of the study site in cardiac CT, and the number of CCTA scans performed per month as independent factors associated with DLP. These findings demonstrate some potential for improving hardware and software in terms of radiation dose effectiveness and for educating CT technicians regarding techniques to reduce radiation dose.

The current PROTECTION I study provides data sufficient to determine a diagnostic reference level for CCTA scans. The diagnostic reference level is typically set at the 75th percentile dose level for a typical-sized patient and for a certain radiological procedure. The diagnostic reference level is not the recommended or preferred dose, but rather an action level at which additional investigation into the dose used should be performed. Reference levels have been shown to lower radiation dose for a diagnostic study over time, as users above the reference level strive to get below it. Consequently, the median dose decreases and the variability in dose is reduced. For CCTA of the coronary arteries in a typical-sized patient, the 75th percentile CTDIvol and DLP values were found to be 69.6 mGy and 1152 mGy × cm, respectively. Accordingly, the current data suggest rounded CTDIvol and DLP values of 70 mGy and 1200 mGy × cm for consideration as diagnostic reference levels for CCTA.

**Limitations**

The definition of tube current is not universally standardized and differs between CT manufacturer, CT models, and software packages. Consequently, it is impossible to assess and analyze the effect of the individual tube current settings within our study. Instead, CTDIvol and DLP values that incorporate the tube current were used for analysis.

The radiation dose associated with coronary calcium scoring, which is performed in some institutions before CCTA, was not assessed in our study. However, compared with CCTA, the radiation dose of calcium scoring represents only a small fraction of the total dose of a cardiac CT study.

The majority of radiation dose data were contributed from European CCTA study sites, followed by Asian and North American CCTA study sites. In addition, the invitation of CCTA sites on the basis of previous publications might have introduced a bias toward more experienced CCTA centers, which might have lowered the overall median DLP. However, the international study design with rather small differences in DLPs between different world regions and the larger proportion of nonacademic CCTA study sites support the notion that the presented data are the best available and most representative results of current international CCTA practice.

**Implications**

Based on the variability in dose levels observed in our study, CT technicians may need to increase their awareness of the radiation dose to which they are exposing their patients during CCTA. With the recording of DLP values and/or an estimation of radiation dose in every CCTA, CT technicians might receive constant feedback on their efforts to keep the dose “as low as reasonably achievable.” In addition, worldwide educational efforts by (1) medical societies, (2) CCTA teaching sites, and (3) CT manufacturers are needed to ensure the appropriate and consistent use of established dose-reduction algorithms where applicable. As CCTA is being used more frequently worldwide for diagnosing coronary artery disease, all strategies for reducing radiation exposure will finally reduce the patient’s lifetime cancer risks. Although the associated risk is small (estimated lifetime attributable risk of death from cancer after an abdominal CT scan is 0.02%16) relative to the diagnostic information for most CT studies, this risk needs to be realized especially when repeated CT scans are being performed. However, prospective randomized trials are needed to demonstrate noninferiority of newer dose-reduction algorithms in terms of diagnostic image quality in appropriately selected patients.

In conclusion, the PROTECTION I study demonstrates that radiation dose of 12 mSv for CCTA is currently comparable with other diagnostic procedures (1.2 × the dose of an abdominal CT study or 600 chest x-rays), but that this dose varies significantly between study sites and CT systems. Additionally, the study demonstrates that radiation exposure can be reduced substantially by uniformly applying the currently available strategies for dose reduction, but these strategies are used infrequently. The selective use of these dose-saving strategies, including a 100-kV scan protocol and the sequential scan mode, were not associated with a decrease in the rate of diagnostic studies in the current observational PROTECTION I study. Consequently, an improved education of physicians and technicians performing CCTA on these dose-saving strategies might be considered to keep the radiation...
dose “as low as reasonably achievable” in every patient undergoing CTA.

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