Radiation Dose Estimates From Cardiac Multislice Computed Tomography in Daily Practice

Impact of Different Scanning Protocols on Effective Dose Estimates

Jörg Hausleiter, MD; Tanja Meyer, MD; Martin Hadamitzky, MD; Ester Huber; Maria Zankl, MSc; Stefan Martinoff, MD; Adnan Kastrati, MD; Albert Schömig, MD

Background—Multislice computed tomography angiography (CTA) is a promising technology for imaging patients with suspected coronary artery disease. Compared with 16-slice CTA, the improved spatial and temporal resolution of 64-slice CTA (0.6- versus 1.0-mm slice thickness and 330- versus 420-ms gantry rotation time) is associated with an increase in radiation dose. The objective of this retrospective investigation was to compare the estimated dose received during 16- and 64-slice CTA in daily practice and to investigate the impact of different scan protocols on dose and image quality.

Methods and Results—Radiation dose was estimated for 1035 patients undergoing coronary CTA. Scanning algorithms with and without an ECG-dependent dose modulation and with a reduced tube voltage were investigated on dose estimates and image quality. In the entire patient cohort, radiation dose estimates were 6.4±1.9 and 11.0±4.1 mSv for 16- and 64-slice CTA, respectively (P<0.01). The reduction in radiation dose estimates ranged between 37% and 40% and between 53% and 64% with the use of ECG-dependent dose modulation and with the combined use of the dose modulation and a reduced tube voltage, respectively. The reduction in dose estimates was not associated with a reduction in diagnostic image quality as assessed by the signal-to-noise ratio and by the frequency of coronary segments with diagnostic image quality.

Conclusions—The increase in spatial and temporal resolution with 64-slice CTA is associated with an increased radiation dose for coronary CTA. Dose-saving algorithms are very effective in reducing radiation exposure and should be used whenever possible. (Circulation. 2006;113:1305-1310.)

Key Words: imaging ■ tomography ■ angiography

Clinical Perspective p 1310

Many of the technical factors that have enhanced image quality, particularly spatial and temporal resolution, also affect the radiation dose received from a CT examination of the heart. The rapid evolution of cardiac CT and its increasing availability, combined with the significance of the CT dose levels, have created a compelling need to assess the impact of different scanning protocols on CT dose. Previous studies have mainly focused on the theoretical and physical aspects of CT dose. Therefore, the aim of the present retrospective study was (1) to estimate the effective dose from cardiac CT angiography in daily practice, (2) to compare the dose estimates from 16- and 64-slice cardiac CT angiography, and (3) to evaluate the impact of 2 different strategies on dose savings and image quality with both scanner types.

Methods

Patients

In this retrospective study, we included 1035 patients in whom contrast-enhanced coronary CT angiography was performed in our interdisciplinary cardioradiologic MSCT laboratory. MSCT-related data and the results of contrast-enhanced CT angiography were collected in a dedicated coronary MSCT reporting system with the use of an Oracle database.
Multislice Spiral Computed Tomography

Contrast-enhanced CT angiography was performed with 16- and 64-slice CT scanner systems (Somatom Sensation Cardiac 16 or 64; both Siemens Medical Solutions; Forchheim, Germany). With 16-slice CT, a collimation of 0.75 mm was used with a gantry rotation time of 420 ms. Additional acquisition parameters were adjusted to individually optimize CT angiographies: pitch range 0.16 to 0.21 and range of tube current 500 to 700 mA. With 64-slice CT, 64 overlapping 0.6-mm slices were acquired per rotation with the use of a focal spot that periodically moved in the longitudinal direction (z-flying focal spot; 0.6-mm collimation and 330-ms gantry rotation time, range of pitch 0.18 to 0.2, and range of tube current 633 to 945 mA). The resulting volume CT dose index (CTDIvol) ranged between 17.6 and 54.6 Gy and between 18.8 and 66.4 Gy for 16- and 64-slice CT, respectively. Contrast dye (350 mg of iodine per milliliter) was injected intravenously at flow rates between 4.0 and 5.0 mL/s. Transaxial images were reconstructed with kernel B30f with a slice width of 1.0 and 0.6 mm for 16- and 64-slice CT, respectively.

Strategies for Reduction of Radiation Dose

An algorithm also referred to as dose pulsing, which modulates the tube current according to the ECG during the spiral scan, was used whenever possible. Cardiac motion is least during diastole and greatest during systole; thus, the image data are most likely sharpest during the diastolic phase. Accordingly, this algorithm reduces the tube current by 80% during systole, in which image reconstruction is not likely to be of interest. Reasons for not using this algorithm were arrhythmias recorded during the preparation time before CT angiography or the need for optimal image quality during the entire cardiac cycle in selected patients.

Another approach for reducing radiation dose is reduction of the tube voltage, because the radiation dose varies with the square of the tube voltage. A reduced voltage may also influence image quality, especially when iodinated contrast media are used. Owing to the high relative atomic number of iodine, the attenuation of iodinated contrast media increases with reduced x-ray energy, which results in a higher contrast between contrast media–filled vascular structures and the perivascular tissue. However, the reduction of radiation dose also correlates with increased image noise and potentially with decreased image quality. Thus, use of the scanning protocol with reduced tube voltage and a compensation for the reduced voltage by increasing the tube current were at the discretion of the coronary CT angiographer.

Assessment of Image Quality

To obtain objective indices of image quality, we determined image noise and contrast- and signal-to-noise ratios for different scanning protocols. Image noise was derived from the standard deviation of the density values (in Hounsfield units) within a large region of interest in the left ventricle. The contrast-to-noise ratio was defined as the difference between the mean density of the contrast-filled left ventricular chamber and the mean density of the left ventricular wall, which was divided by image noise. The signal-to-noise ratios were assessed in the proximal segments of the left and right coronary artery. This parameter, which may be more relevant in the detection of lumen narrowings and of atherosclerotic plaque burden, was calculated from the mean density values of the contrasted coronary lumen divided by the standard deviation of these density values. With 16-slice CT, image-quality parameters were obtained from 1.0-mm slices, whereas the slice thickness was 0.6 mm for 64-slice CT angiographic images.

Two reviewers independently evaluated the coronary CT angiography by assessment of axial slices and 3 thin-slab maximum intensity projections. Orientated along the heart axis, the thin-slab (5-mm thickness, 1-mm increment) maximum intensity projections were reconstructed perpendicular to each other. The coronary artery tree was segmented according to modified American Heart Association classification, and the diagnostic image quality was investigated for each segment with a vessel diameter of at least 2.0 mm by caliper measurements. The grading criteria for image quality were as follows: Good diagnostic quality was defined for coronary segments without or with moderate calcifications, without motion artifacts, and with good vessel opacification. Limited image quality, but still diagnostic for the evaluation of lumen stenosis, was defined in the presence of moderate motion artifacts or a reduced vessel opacification. Coronary segments with extensive calcifications, stent placement, extensive motion artifacts, or poor opacification were considered nondiagnostic.

The scan protocol with the use of 120-kilovolt peak (kVp) tube voltage and without application of the ECG-dependent dose modulation was defined as the standard scan protocol for both 16- and 64-slice CT scanners. All image-quality parameters obtained with the algorithms for dose savings were compared with the parameters of the standard scan protocol. Because of the differences in image acquisition between 16- and 64-slice CT systems, no comparisons between the 2 systems were performed.

Statistical Analysis

Results are expressed as counts (or proportions in percentages) or as mean±SD. For discrete variables, comparisons of the 2 groups were performed with the x² test or Fisher’s exact test, if appropriate. Continuous variables were analyzed with an unpaired, 2-tailed t test. Statistical significance was accepted for 2-sided probability values <0.025 (the usual α-level of 0.05 corrected for 2 planned comparisons between the standard CT scanning protocol and the 2 investigated protocols for effective dose reduction according to the Bonferroni method).

The authors had full access to the data and take responsibility for its integrity. All authors have read and agree to the manuscript as written.

Results

Sixteen-Slice Versus 64-Slice CT Angiography

Assessment of the effective radiation dose of cardiac CT angiography was possible in a total of 1035 patients. Sixteen- and 64-slice CT angiography was used in 436 (42.1%) and 599 (57.9%) patients, respectively. Table 1 summarizes the patient characteristics of both groups. With 64-slice CT, significantly more patients did undergo cardiac CT angiography for evaluation of bypass grafts or for assessment of coronary artery disease due to an elevated cardiovascular risk. Fewer patients were studied with 64-slice CT before a planned electrophysiology study or owing to a positive stress test in the absence of chest pain. The algorithm of ECG-dependent dose modulation was used in the majority of patients (82.2% of all patients) without significant difference between 16- and 64-slice CT, whereas the lower tube voltage of 100 kV had been used in 34.4% and 11.4% with 16- and 64-slice CT, respectively (P<0.01). The overall effective dose estimate of cardiac CT angiography resulted in 6.4±1.9 and 11.0±4.1 mSv with 16- and 64-slice CT, respectively (P<0.01).
modulation and 100-kV scans with dose modulation, each with dose estimates, an effective dose of 10.6 \pm 1.2 mSv was estimated for the 100-kV protocol with 16- and 64-slice CT, respectively. When we compared these estimates with the 120-kV protocol without ECG-dependent dose modulation, the overall relative dose reductions ranged between 53% and 64% (P<0.001 for 16- and 64-slice CT; Figure, panel A).

### Image Quality

Image quality was assessed quantitatively by image noise, contrast-to-noise ratio, and signal-to-noise ratio. Although image noise did not differ between CT angiographies performed with and without ECG-dependent dose modulation, the use of the 100-kV protocols resulted in significantly increased image noise compared with 16- and 64-slice CT (Figure, panel C). Signal-to-noise and contrast-to-noise ratios did not differ between scan protocols when we compared these estimates with the 120-kV protocol without ECG-dependent dose modulation and with the 100-kV protocols with 16- and 64-slice CT. Table 2 summarizes the patient characteristics, relevant MSCT results, and image quality for the estimate of the effective radiation dose in more detail.

### Table 2. Subgroup of Patients Studied With Different Scanning Protocols

<table>
<thead>
<tr>
<th></th>
<th>16-Slice CT Without Dose Modulation</th>
<th>16-Slice CT With Dose Modulation</th>
<th>64-Slice CT Without Dose Modulation</th>
<th>64-Slice CT With Dose Modulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of patients</td>
<td>30</td>
<td>50</td>
<td>50</td>
<td>50</td>
</tr>
<tr>
<td>Male sex</td>
<td>20 (67)</td>
<td>33 (66)</td>
<td>34 (68)</td>
<td></td>
</tr>
<tr>
<td>Body mass index, kg/m²</td>
<td>26.9 ± 3.2</td>
<td>27.5 ± 4.5</td>
<td>26.4 ± 2.9</td>
<td></td>
</tr>
<tr>
<td>Heart rate, bpm</td>
<td>61.3 ± 11.3</td>
<td>60.7 ± 9.5</td>
<td>57.8 ± 5.3</td>
<td></td>
</tr>
<tr>
<td>Scan length, mm</td>
<td>128.2 ± 11.8</td>
<td>125.9 ± 9.2</td>
<td>124.0 ± 7.7</td>
<td></td>
</tr>
<tr>
<td>Tube current, mA</td>
<td>510.0 ± 40.3</td>
<td>304.5 ± 42.3*</td>
<td>387.6 ± 18.9*</td>
<td></td>
</tr>
<tr>
<td>Pitch</td>
<td>0.18 ± 0.01</td>
<td>0.18 ± 0.01</td>
<td>0.21 ± 0.02*</td>
<td></td>
</tr>
<tr>
<td>CTDIvol, Gy</td>
<td>42.1 ± 3.6</td>
<td>25.2 ± 2.9*</td>
<td>19.4 ± 1.0*</td>
<td></td>
</tr>
<tr>
<td>Image noise, HU</td>
<td>29.3 ± 6.9</td>
<td>28.3 ± 6.8</td>
<td>36.9 ± 9.4*</td>
<td></td>
</tr>
<tr>
<td>Contrast-to-noise ratio</td>
<td>7.3 ± 3.1</td>
<td>8.1 ± 3.4</td>
<td>8.8 ± 2.9</td>
<td></td>
</tr>
<tr>
<td>Signal-to-noise ratio</td>
<td>11.1 ± 3.9</td>
<td>11.9 ± 4.3</td>
<td>11.9 ± 3.7</td>
<td></td>
</tr>
<tr>
<td>Dose estimate, mSv</td>
<td>10.6 ± 1.2</td>
<td>6.4 ± 0.9*</td>
<td>5.0 ± 0.3*</td>
<td></td>
</tr>
</tbody>
</table>

*P<0.025 for comparison with 16-slice CT scanning protocol using 120 kV without ECG-dependent dose modulation.
†P<0.025 for comparison with 64-slice CT scanning protocol using 120 kV without ECG-dependent dose modulation.
To further assess the impact of different scan protocols on image and diagnostic quality, a qualitative assessment of coronary segments was performed. A total of 3492 coronary segments were evaluated for size, good or limited diagnostic quality, or nondiagnostic quality. Of these, 694 (19.9%) coronary segments presented with a small caliper and were not evaluated for diagnostic image quality. For the remaining segments, no deterioration of diagnostic image quality was observed with utilization of ECG-dependent dose modulation and of the 100-kV protocols with 16- and 64-slice CT (Figure, panel D; Table 3). The predominant reasons for nondiagnostic image quality were extensive motion artifacts or extensive coronary calcifications.

**Discussion**

Contrast-enhanced coronary MSCT has been introduced for the assessment of calcified plaque burden and the detection of coronary stenosis and noncalcified plaques.\textsuperscript{1-3} Because of its noninvasive nature, coronary CT angiography is appreciated as an attractive alternative for the assessment of coronary artery disease. Despite the lack of data for most indications, cardiac CT angiography is increasingly being used (1) to screen selected patients for coronary atherosclerosis, (2) to assess the precise cardiac and pulmonary vein anatomy before electrophysiology procedures, (3) to rule out significant lumen narrowings in patients with suspected coronary artery disease, and (4) to study the success of myocardial revascularization procedures such as bypass grafting or coronary stenting.\textsuperscript{8-12} However, the potential advantages of coronary CT angiography over traditional methods for the assessment of coronary artery disease have to be weighed against the potential hazards associated with this method. Many clinicians and researchers may yet be unfamiliar with the amount of radiation exposure that is received during CT angiography and how imaging protocols may differ between the various scanner types that are currently used. Therefore, the present study investigated effective dose estimates and the impact of different scanning protocols for coronary CT angiography in a large group of patients.

The present study demonstrates that the effective dose for cardiac MSCT scanning in daily practice is estimated to be 6.4±1.9 and 11.0±4.1 mSv with 16- and 64-slice CT, respectively. The increase in dose estimates with the 64-slice technology is explained by the higher spatial and temporal resolution achieved with current CT scanner technology. The

---

**TABLE 3. Qualitative Assessment of Diagnostic Image Quality in the Subgroup of Patients Studied With Different Scanning Protocols**

<table>
<thead>
<tr>
<th></th>
<th>16-Slice CT</th>
<th>64-Slice CT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>120 kV Without Dose Modulation</td>
<td>120 kV With Dose Modulation</td>
</tr>
<tr>
<td>Total No. of coronary segments</td>
<td>368</td>
<td>668</td>
</tr>
<tr>
<td>Small coronary segments</td>
<td>78 (21.2)</td>
<td>156 (23.4)</td>
</tr>
<tr>
<td>Segments assessed for diagnostic image quality</td>
<td>290</td>
<td>512</td>
</tr>
<tr>
<td>Segments with good diagnostic quality</td>
<td>206 (71.0)</td>
<td>448 (87.5)</td>
</tr>
<tr>
<td>Segments with limited diagnostic quality</td>
<td>7 (2.4)</td>
<td>8 (1.6)</td>
</tr>
<tr>
<td>Nondiagnostic segments</td>
<td>77 (26.6)</td>
<td>56 (10.9)</td>
</tr>
</tbody>
</table>

Data are n (%). Small coronary segments were defined by a vessel diameter <2.0 mm.
high spatial resolution, which is a prerequisite for accurate assessment of coronary artery narrowings and atherosclerotic plaque burden, increased from 16- to 64-slice CT owing to a decrease in collimation and the respective slice width (collimation 0.75 and 0.6 mm with 16- and 64-slice CT, respectively). To maintain a comparable image quality with the reduced slice width, the number of photons received by the detector array is usually increased by an escalation in the tube current. Such an escalation in tube current also results in increases in radiation exposure and in effective dose estimates. Furthermore, an increase in temporal resolution is achieved with newer 64-slice CT scanners by an increase in gantry rotation speed. To avoid a decrease in image quality, the rate of photons received by the detector array must also be increased, and therefore, the tube current is further increased, which results in a higher effective dose estimate.13 When one compares 16- and 64-slice CT dose estimates, another factor needs to be taken into account. With the increased number of simultaneously acquired slices, the scanning time of 64-slice CT is reduced, which allows for an increase in the scan length acquired with a single short breath hold. This development is also reflected in the increased number of patients who were scanned with longer scan ranges for the evaluation of bypass graft patency in the present study with 64-slice CT.

In the second part of this study, we investigated the impact of 2 different algorithms for reduction of the estimated radiation dose with both scanner types. The first algorithm used allows for ECG-dependent modulation of the tube current. Image reconstruction of cardiac MSCT examinations is usually performed in ventricular mid diastole, because cardiac motion and thus blurring of cardiac structures due to motion artifacts is least during that period of the cardiac cycle. Projection data that do not correspond to the desired time window of mid diastole are usually ignored by this postprocessing technique, called “retropective gating.” Therefore, the algorithm of ECG-dependent dose modulation allows for a high tube current with optimal image quality during mid diastole, while reducing the tube current by 80% in the remainder of the cardiac cycle. Because the onset of tube current reduction is based on the average of the 3 prior RR intervals, the algorithm may inappropriately reduce the current in the event of arrhythmias such as premature extra beats. Therefore, this algorithm may not be useful in patients with arrhythmias or in patients in whom the best image quality is needed throughout the entire cardiac cycle. However, such patients constitute a minority of patients studied currently by MSCT. In fact, the present study demonstrates that this algorithm had been used in 82.2% of patients investigated in our cardioradiologic MSCT laboratory. Although we cannot rule out that unexpectedly occurring premature extra beats deteriorated diagnostic image quality when the ECG-dependent dose algorithm was used, the likelihood of such arrhythmias occurring is very low, and the investigated parameters for image quality did not differ between patients in whom this algorithm was used or not used (Table 2). When we compared patients with typical coronary MSCT investigations, the use of this algorithm resulted in a significant reduction of the radiation dose estimate of 40% and 37% with 16- and 64-slice CT, respectively. Therefore, the algorithm for ECG-dependent dose modulation represents a very effective tool for limiting radiation dose in the vast majority of patients undergoing cardiac MSCT studies.

Recently, it has been established that lower tube voltages may allow for a reduction in effective dose in pediatric CT investigations without affecting diagnostic image quality.14 The decrease in radiation dose is achieved because the radiation dose varies with the square of the kilovoltage. Furthermore, the decreased tube voltage leads to increased opacification of vascular structures during contrast-enhanced CT angiography owing to an increase in the photoelectric effect and a decrease in Compton scattering.15 Therefore, we investigated in a further step the impact of a lower tube voltage on the effective dose estimates and image quality during cardiac 16- and 64-slice CT scanning. Because of a later availability of this scan protocol on the 64-slice CT system, the 100-kV tube voltage scan protocol was used less frequently in the present patient cohort. Compared with cardiac CT studies performed with 120 kV and without ECG-dependent dose modulation, the use of the reduced voltage of 100 kV together with ECG-dependent dose modulation resulted in the present study in an effective dose reduction of 53% and 64% with 16- and 64-slice CT, respectively. The small difference in relative dose reduction between 16- and 64-slice CT is mainly based on small variations in other scan parameters and in studied patient groups, including differences in pitch, scan length, and heart rate. As a consequence of the above-mentioned physical aspects, the signal improved with the lower tube voltage, but the image noise also increased significantly. With the increase of both parameters, the ratios for signal-to-noise and contrast-to-noise did not differ between scan protocols within each CT system. For noncardiac CT studies with kilovoltage reduction, an increase of the tube current by 50% has been proposed to maintain image quality and to reduce the dose estimates at the same time16; however, a further increase in tube current is limited with the available standard protocols for cardiac CT scanning on the studied CT scanners. Therefore, a tradeoff between dose saving and increased image noise has to be made with current cardiac CT protocols.

The best balance between optimal dose savings and maintained diagnostic, rather than esthetic, image quality for coronary CT angiographic investigations is difficult to assess; the present study compared the frequency of coronary segments with good and limited diagnostic image quality for the detection of stenosis between different scan protocols. In this qualitative analysis of image quality, no deterioration of diagnostic image quality was detected for scan protocols with the ECG-dependent dose modulation and with the 100-kV protocols with 16- and 64-slice CT. However, the value of this analysis is limited by a potential selection bias of used scan protocols, eg, the use of a 120-kV scan protocol without ECG modulation for patients with arrhythmias, who are likely to present with more nondiagnostic coronary segments, even when no dose-saving algorithms were applied. Finally, the impact of dose-saving algorithms on the detection of calcified and noncalcified plaques is unknown. Therefore, further studies are needed to investigate the balance between dose savings and maintained diagnostic image quality for coronary CT angiographic investigations.

Study Limitations
This study was not designed to compare diagnostic image quality and the assessibility of coronary segments between the 2
investigated CT systems because of the inherent differences in image acquisition. However, in the present study, a higher percentage of coronary segments were assessable by 64-slice CT owing to its higher spatial and temporal resolution. This finding may imply that the improvement in resolution is more important for the assessibility and discernment of coronary segments and stenoses than the differences in quantitative image-quality parameters. Therefore, further studies are needed to investigate the impact of temporal and spatial resolution, as well as of image-quality parameters, on the sensitivity and specificity of coronary stenosis detection by CT angiography to justify the increase in radiation dose when 64-slice CT is used.

In summary, it is important to be aware of the magnitude of the radiation dose received from coronary CT scanning and to realize that a careful selection of CT scanning protocols is needed to keep the radiation exposure “as low as reasonably achievable (ALARA)”. Furthermore, cardiac CT angiographies should be performed with new scanning techniques that allow for a reduction in effective dose estimates, such as ECG-dependent dose modulation and reduced tube voltage, whenever the use of these techniques is possible without a deterioration of diagnostic image quality. Finally, future studies are needed to identify patients who truly benefit from coronary CT angiography to justify the potential hazards of radiation exposure.

Acknowledgments

We are indebted to the medical and technical staff members of the computed tomography laboratories for their invaluable contribution and in particular to U. Lang, C. Schwarzer, and B. Child (all RT) for their expert technical assistance.

Disclosures

None.

References


