Noninvasive Coronary Angiography by Retrospectively ECG-Gated Multislice Spiral CT

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Background—We investigated the applicability and image quality of contrast-enhanced coronary artery visualization by multislice spiral CT using retrospective ECG gating.

Methods and Results—Twenty-five patients in sinus rhythm (significant coronary artery stenoses ruled out by invasive angiography) were studied with a multislice spiral CT (Siemens SOMATOM Volume Zoom). In inspiration (mean breathhold, 37 seconds), a volume data set of the heart was acquired (intravenous contrast agent; 4×1-mm slice thickness; 500-ms rotation; table feed, 1.5 mm/360°). Simultaneous recording of the ECG permitted retrospective reconstruction of contiguous cross sections in intervals of 1 mm at any desired interval of the cardiac cycle. The mean duration of the image reconstruction window was 185 ms. Next to 3-dimensional reconstructions of the heart and coronary arteries, multiplanar reconstructions were rendered to determine the visualized length of the coronary arteries, the contrast-to-noise ratio, and the correlation of coronary artery diameters to quantitative coronary angiography.

Conclusions—The coronary arteries could be visualized over long segments (left main, 9±4 mm; left anterior descending, 112±34 mm; left circumflex, 80±29 mm; right coronary artery, 116±33 mm). On average, 78±16% of these distances were visualized free of motion artifacts. The mean contrast-to-noise ratio was 9.3±3.3. Coronary artery diameters in multislice spiral CT showed close correlation to quantitative coronary angiography (CT, 3.3±1.0 mm; angiography, 3.2±0.9 mm; mean difference, 0.38 mm; r=0.86). Contrast-enhanced multislice spiral CT permits visualization of the coronary artery lumen. Further studies are necessary to determine whether image quality is sufficient to reliably detect coronary artery stenoses. (Circulation. 2000;102:2823-2828.)

Key Words: imaging ■ coronary disease ■ tomography

X-ray coronary angiography is considered the diagnostic standard for establishing the presence of coronary artery stenoses. Because this technique has limitations as a result of its invasive nature with a small, nevertheless not negligible, procedure-related mortality (0.15%) and morbidity (1.5%) rates1,2 and relatively high cost, attempts have been made to image the coronary artery lumen with noninvasive methods. MRI3–10 and especially electron-beam tomography (EBT)11–18 have been successfully used to visualize the coronary arteries. Although mechanical CT has been successfully used to demonstrate the patency of coronary artery bypass grafts,19–21 the temporal resolution of conventional CT scanners has so far not been sufficient to visualize native coronary arteries. During the past years, CT scanners with gantry rotation times <1 second have been introduced. By using retrospective ECG gating, cardiac CT imaging can be performed with data acquisition windows that are shorter than the rotation time of the scanner.22 This approach has been used to detect and quantify coronary calcification,23,24 and one case report of a stenosis of the left anterior descending coronary artery visualized by contrast-enhanced spiral CT with a temporal resolution of 0.4 second has been published.25 The latest generation of spiral CT scanners offers rotation times of 500 ms and the possibility to simultaneously acquire up to 4 parallel slices. The lower scan times and especially multislice acquisitions, in combination with retrospective ECG gating, allow the data acquisition window to be shortened even further.26–28 We investigated the applicability and image quality of contrast-enhanced coronary artery visualization using a multislice CT scanner of the latest generation and a new ECG-gated image reconstruction algorithm, 180° Multislice Cardiac Interpolation (180°MCI), the theoretical basis of which and advantage over other reconstruction algorithms have been described in detail elsewhere.26,27

Methods

Twenty-five consecutive patients (16 men and 9 women; mean age, 56 years; range, 39 to 80 years) were investigated. In all patients,
invasive x-ray coronary angiography had been performed, and hemodynamically relevant coronary artery stenoses (>50% diameter reduction) had been ruled out. All patients had sinus rhythm (heart rate, 51 to 115 bpm; mean, 77 bpm) and were in a clinically stable condition. The mean weight of the patients was 80.2 kg (range, 56 to 115 kg). All patients gave written informed consent, and the study protocol was approved by the institutional review board.

**Multislice Spiral CT**

Multislice spiral CT (SOMATOM Volume Zoom, Siemens AG) was performed 1 to 3 days after invasive angiography. Medications were maintained between the invasive angiogram and the multislice spiral CT study. All image acquisitions were performed in inspiratory breathhold preceded by mild hyperventilation. First, a noncontrast localization scan was performed that yielded an anteroposterior view of the chest; it was used to position the imaging volume for coronary artery imaging, which extended from the carina to ~1 cm below the diaphragmatic face of the heart. In a second step, a bolus of 20 mL of contrast agent (Iohexol, Ultravist350, Schering AG) was injected intravenously at 4 mL/s via an 18-gauge catheter placed in the cubital vein. After a delay of 10 seconds, a sequence of 10 axial images at the level of the carina was acquired with an interval of 2 seconds between subsequent images. From the time interval between contrast agent injection and acquisition of the image with peak attenuation in the aortic root, the contrast agent transit time was determined. In a third step, the volume data set for coronary artery visualization was acquired in spiral mode, with simultaneous acquisition of 4 parallel slices with 1.0-mm collimation each. The gantry rotation time was 500 ms, and the patient table was continuously advanced at 3.0 mm/s. The tube current was 150 mA. During the scan, the patient’s ECG was digitized and continuously recorded.

Contrast agent (160 mL) was injected into the cubital vein at 4 mL/s, and the CT scan was initiated with a delay according to the previously determined contrast agent transit time. Using the PC program WinDose (Wellhöfer Dosimetrie/Scanditronix Medical), we estimated the effective radiation dose of the complete investigation to be between 3.9 mSv (men) and 5.8 mSv (women).

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**Image Reconstruction**

The CT raw data were transferred to an offline, PC-based workstation. Next to ungated image reconstruction with a conventional spiral CT algorithm (180° Linear Interpolation; 180°LI),[20] cross-sectional images with a slice thickness of 1.2 to 1.4 mm were reconstructed in 1-mm intervals with the new algorithm 180°MCI.[27] In short, the algorithm collects spiral data from successive heart beats by applying a filter function not only in the z direction (along the patient’s longitudinal axis) but also in the heart phase. The planar data set acquired by this means then undergoes the normal, filtered back-projection process for image reconstruction in CT. The width of the image reconstruction window is expressed through the full-width tenth-maximum of the phase contribution profile,[27] which strongly depends on the patient’s heart rate and was between 125 and 243 ms in our study (mean, 185±41 ms; see Figure 1). The field of view was 180 mm, with an image

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**Figure 1.** Relationship between heart rate and duration of image reconstruction window (full-width tenth-maximum of heart phase contribution profile). RR indicates R-wave to R-wave interval.

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**Figure 2.** Cross-sectional images acquired by contrast-enhanced multislice spiral CT in patient with heart rate of 77 bpm. A, Ungated image (reconstruction algorithm, 180°LI; 500-ms image acquisition time) at level of left main and proximal left anterior descending coronary arteries showing moderate motion artifacts. B, Retrospectively ECG-gated image at same level using reconstruction window of 215 ms centered at 70% of cardiac cycle. Decreased motion artifacts permit clearer visualization of proximal left anterior descending coronary artery (arrow). C, Ungated image (500-ms acquisition time) at level of mid right coronary artery. Severe motion artifacts prevent visualization of right coronary artery. D, Retrospectively ECG-gated image at same level using reconstruction window of 215 ms centered at 50% of cardiac cycle. Decreased motion artifacts permit clear visualization of right coronary artery (large arrow) and side branch (small arrow). Note also improved visualization of left anterior descending coronary (arrowhead) and left circumflex coronary (open arrow) arteries.

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**Distribution of Optimal Positions of the Image Reconstruction Window Relative to the Cardiac Cycle**

<table>
<thead>
<tr>
<th>Center of Image Reconstruction Window With Least Motion Artifacts, % Cardiac Cycle</th>
<th>Patients, n</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>10%</td>
</tr>
<tr>
<td>Left main and left anterior descending coronary arteries</td>
<td>0</td>
</tr>
<tr>
<td>Left circumflex coronary artery</td>
<td>0</td>
</tr>
<tr>
<td>Right coronary artery</td>
<td>0</td>
</tr>
</tbody>
</table>
matrix of 512×512 pixels. For each patient, 10 data sets were created. For the first data set, the image acquisition window was centered around the peak of the R wave. For the second data set, the center was positioned at 10% of the R-R interval, and for the subsequent data sets, the center of the image acquisition window was moved toward the end of the cardiac cycle in increments of 10%. Because reconstruction of one cross-sectional image required ~2 seconds, 30 to 45 minutes was necessary to create all 10 data sets. All image data sets were inspected concerning the presence of motion artifacts, and for each coronary artery, the data set that contained the fewest motion artifacts was chosen for further evaluation.

Data Evaluation

The reconstructed images were transferred to a commercially available image processing workstation (NetraMD, ScImage) and evaluated by a single blinded observer. As measures of image quality, the visualized length of each coronary artery, the contrast-to-noise ratio (CNR), and the correlation of coronary artery diameters in multislice spiral CT and in quantitative x-ray coronary angiography were determined. For each artery (left main, left anterior descending, left circumflex, and right coronary artery), a curved multiplanar reconstruction was rendered as previously described. In the multiplanar reconstructions, the visualized length of each coronary artery was measured. In addition, the length of the vessel segments that were visually judged to be free of motion artifacts was determined. The CNR was determined for each coronary artery by measuring the mean CT density within the proximal artery lumen and the mean CT density in a region of interest in the connective tissue immediately next to the coronary artery and dividing the respective difference by the image noise (SD of CT density in a region of interest placed in the aortic root). Finally, the diameters of the left main and proximal left anterior descending, left circumflex, and right coronary artery were determined immediately before or after bifurcation points that could be identified in both multislice spiral CT and invasive coronary angiography. Diameters were measured by use of the principle of “full-width half-maximum”:

In addition, 3-dimensional reconstructions were created with the “volume rendering technique” after manual segmentation of the data sets to remove structures that would obstruct the view onto the coronary arteries, such as the chest wall, pulmonary trunk, and atrial appendages.

Figure 3. Three-dimensional reconstruction of heart and coronary arteries obtained with volume rendering technique. By manual segmentation of cross-sectional images, pulmonary trunk and atrial appendages were removed to permit visualization of proximal coronary arteries. A, View from anterior face of heart showing short left main and left anterior descending coronary arteries (large arrow), as well as left circumflex coronary artery (small arrow; image reconstruction window centered at 80% of cardiac cycle). B, Inferior and lateral view showing right coronary artery (arrow; image reconstruction window centered at 70% of cardiac cycle).

Figure 4. Three-dimensional reconstruction (volume rendering technique) showing anomalous origin of right coronary artery (small arrow) from left sinus of valsalva, as well as normal left main and left anterior descending coronary arteries (large arrow; image reconstruction window centered at 70% of cardiac cycle).
Quantitative Coronary Angiography
The x-ray coronary angiograms of all patients were evaluated by means of QCA. The tip of the angiography catheter was used for calibration, and the vessel diameters of the coronary segments corresponding to those used for determination of the artery diameter in multislice spiral CT were measured in 2 orthogonal planes with automated contour detection. The mean of the 2 obtained values was considered to represent the actual vessel diameter at that site. Diameters were measured at the same time instant in the cardiac cycle as in multislice spiral CT.

Results
Multislice spiral CT was performed successfully and without complications in all 25 patients. The mean duration of the complete imaging procedure was 17±3 minutes. The mean craniocaudal distance of the volume data set needed to cover the heart was 110±11 mm (range, 90 to 137 mm). The mean duration of the breathhold therefore was 37±4 seconds (range, 30 to 46 seconds). Three patients were unable to hold their breath during the complete duration of the scan; their data were included in the analysis.

Using retrospective ECG gating with the image reconstruction algorithm 180°MCI, we could suppress cardiac motion artifacts in most images (see Figure 2). The cardiac phase that yielded optimal image quality varied strongly from patient to patient and between different coronary arteries. For the left main and left anterior descending coronary arteries, optimal image quality was usually achieved if the data acquisition window was centered at 70% or 80% of the cardiac cycle, whereas for the left circumflex and right coronary arteries, the most frequent “optimal” position of the data acquisition window was at 50% of the cardiac cycle (see the Table). In 3-dimensional reconstructions, it was possible to visualize the anatomy of the heart and coronary arteries (see Figures 3 and 4). The mean visualized length of the left main coronary artery was 9±4 mm (range, 4 to 17 mm). The mean visualized length of the left anterior descending coronary artery was 112±34 mm (range, 52 to 155 mm); left circumflex coronary artery, 80±29 mm (range, 22 to 139 mm); and right coronary artery, 116±33 mm (range, 45 to 176 mm). Artifacts caused by coronary artery motion were not always fully suppressed and usually affected the mid right coronary artery and distal segments of the left anterior descending coronary artery and left circumflex coronary artery (see Figure 5). Although the left main coronary artery was free of visible motion artifact in all cases, the mean proportion of the left anterior descending coronary artery that was visualized free of motion artifact was 79±16% (range, 55% to 100%). The mean proportion of the left circumflex coronary artery that was visualized free of motion artifact was 79±17% (range, 41% to 100%), and on average, the right coronary artery could be visualized free of motion artifact over 75±14% (range, 54% to 100%) of its entire length.

The mean CNR determined for the proximal coronary arteries was 9.3±3.3 (left main, 8.9±4.1; left anterior descending, 9.9±3.4; left circumflex, 9.3±2.7; and right coronary artery, 9.3±2.8).

Coronary artery diameters were compared between multislice spiral CT and QCA at 100 points (see Figure 6). The mean coronary artery diameter in multislice spiral CT was 3.3±1.0 mm (range, 1.5 to 7.6 mm); the mean diameter in QCA was 3.2±0.9 mm (range, 1.6 to 6.2 mm). The mean absolute difference between the CT and angiographic measurement was 0.38±0.35 mm (range, 0.0 to 1.4 mm). There was no significant difference between diameters in QCA and multislice spiral CT. The slope of the regression line was 0.87, the intercept was 0.32, and the correlation coefficient was 0.86.
Discussion

Reliable noninvasive visualization of the coronary artery lumen through the use of mechanical CT scanners has so far not been possible because of the limited temporal resolution that conventional CT systems provide. The latest generation of spiral CT scanners, however, allows continuous acquisition of data with 4 parallel detectors and, with the use of the patient’s ECG, which is stored with the CT data, retrospective reconstruction of cross-sectional images of the heart with a data acquisition window that is shorter than the rotation time of the CT scanner’s gantry.26-28 We investigated the clinical applicability and image quality of retrospectively ECG-gated cardiac imaging using a multislice spiral CT scanner in a group of patients with sinus rhythm and no significant stenoses of the coronary arteries. We could demonstrate that multislice spiral CT with retrospective ECG gating and a new, sophisticated image reconstruction algorithm (180°MCI) permits visualization of the coronary arteries with high image quality. The coronary arteries could be visualized over longer segments than previously reported for early studies by EBT12 and MRI.3–6,8 The CNR achieved for the proximal coronary arteries was approximately equal to that

Figure 6. Measurement of vessel diameters in multislice spiral CT and QCA. A, Multiplanar reconstruction of left main (small arrow) and left anterior descending coronary arteries (large arrow; arrowhead shows diagonal branch). B, Enlarged segment indicated by box. Multiplanar reconstruction is displayed with window of 1 Hounsfield unit and level of 158 Hounsfield units, corresponding to one half the maximum attenuation within lumen of left anterior descending coronary artery in this segment. Vessel diameter is then measured immediately proximal to origin of diagonal branch (arrows). Vessel diameter here is 0.34 mm. C, Corresponding measurement of vessel diameter in QCA (0.35 mm; only 1 projection shown). D, Correlation between vessel diameters measured in multislice spiral CT (MSCT) and QCA. Correlation coefficient is 0.86.
reported for EBT.12 The high spatial resolution of multislice spiral CT is expressed through the fact that vessel diameters correlated closely to invasive, x-ray coronary angiography. However, motion artifacts resulting from rapid coronary artery motion were not completely eliminated and frequently affected the mid sections of the right coronary artery and the distal segments of the left anterior descending and left circumflex coronary artery. This may limit the applicability of the method, and further studies are necessary to determine whether motion artifacts can be sufficiently suppressed to permit reliable detection of significant coronary artery stenoses.

One major drawback of retrospectively ECG-gated spiral CT is the fact that radiation is continuously applied, whereas image reconstruction is restricted to data acquired during only a fraction of the cardiac cycle. It is doubtful whether prospective triggering algorithms—yet to be developed—would lead to a substantial reduction in radiation exposure, because the optimal positioning of the image reconstruction window used varies from patient to patient and between the different coronary arteries. Based on our data, only a relatively small portion of the cardiac cycle (≈20%) could potentially be excluded from data acquisition. Also, coronary artery visualization by spiral CT requires intravenous injection of iodinated contrast agent, which may lead to side effects and necessitates perfect timing of image acquisition to contrast injection. Minor reductions in the amount of contrast injection could be achieved by exactly adapting the amount of contrast used to the duration of data acquisition, which depends on the cranio-caudal distance of the volume data set, instead of using a standard dose of 160 mL as we did in our study protocol. Another limitation is the relatively low breathhold. At the cost of increased slice thickness, however, the speed of table movement could be increased, leading to a shorter overall scan duration required to cover the volume of the heart. Further investigations are necessary to determine the optimal balance between breathhold duration and slice thickness, which translates into image resolution along the patient’s longitudinal axis.

In conclusion, multislice spiral CT with retrospective ECG gating is an interesting new approach for noninvasive coronary artery imaging. It could be demonstrated that the coronary arteries can be visualized with high spatial resolution and good overall image quality, although artifacts caused by motion, especially of the right coronary artery, can so far not be sufficiently eliminated. In the future, the accuracy of this approach concerning the detection of coronary artery stenoses will have to be determined, and the method needs to be compared against other evolving and established techniques for coronary artery visualization, such as MRI and EBT.

References

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