Coronary artery bypass grafts: ECG-gated multi-detector row CT angiography--influence of image reconstruction interval on graft visibility

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Abstract

PURPOSE: To evaluate the influence of different reconstruction intervals of retrospectively electrocardiographically (ECG)-gated multi-detector row computed tomographic (CT) angiography on image quality of different segments of various types of coronary artery bypass grafts. MATERIALS AND METHODS: Twenty consecutive patients with 62 grafts underwent retrospectively ECG-gated four-channel multi-detector row CT angiography and conventional coronary angiography. Raw helical CT data were reconstructed at 0%-90% of the cardiac cycle in increments of 10%. Each graft was separated into three segments (proximal segment, graft body, and distal anastomosis). Three graft types were identified according to site of distal anastomosis. Two readers assessed image quality of segments and graft types. Effective radiation dose was calculated. RESULTS: Best image quality of all segments was obtained at a reconstruction interval of 50%-70% of the cardiac cycle. Image quality of the proximal segment did not vary significantly with different reconstruction intervals (analysis of variance, P = .8), whereas image quality of the graft body and distal anastomosis changed significantly with varying reconstruction intervals (P < .001). Distal anastomosis and body of types 1 and 2 grafts were best seen at 60%-70% of the cardiac cycle, whereas distal anastomosis and body of type 3 grafts were best visualized at 50%. Accuracy of CT angiography for detection of graft patency was 94% for reader 1 and 95% for reader 2. Effective dose for CT was 11.4 mSv for both men and women. Mean effective dose for angiography was 2.1 mSv for men and women. CONCLUSION: Optimal selection of reconstruction interval improves image quality of the graft body and of distal anastomosis in particular.
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RESULTS: Best image quality of all segments was obtained at a reconstruction interval of 50%–70% of the cardiac cycle. Image quality of the proximal segment did not vary significantly with different reconstruction intervals (analysis of variance, \( P = .8 \)), whereas image quality of the graft body and distal anastomosis changed significantly with varying reconstruction intervals (\( P < .001 \)). Distal anastomosis and body of types 1 and 2 grafts were best seen at 60%–70% of the cardiac cycle, whereas distal anastomosis and body of type 3 grafts were best visualized at 50%. Accuracy of CT angiography for detection of graft patency was 94% for reader 1 and 95% for reader 2. Effective dose for CT was 11.4 mSv for both men and women. Mean effective dose for angiography was 2.1 mSv for men and women.

CONCLUSION: Optimal selection of reconstruction interval improves image quality of the graft body and of distal anastomosis in particular.

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imaging modality is desirable for evaluation of patients suspected of having graft stenosis or occlusion.

In the past, single–detector row helical computed tomography (CT) and electron-beam CT have been applied for evaluation of graft patency. The limited temporal resolution with consecutive motion artifacts, however, has rendered single–detector row helical CT of little value, particularly for the assessment of distal anastomosis of coronary artery bypass grafts (S). Electron-beam CT is not widely available, and technical trade-offs may have hampered routine use for this purpose.

The use of multi–detector row CT is gaining increasing acceptance for noninvasive cardiac imaging. Several studies have demonstrated successful application of multi–detector row CT angiography for assessment of coronary artery disease and evaluation of cardiac valves (6–10). Ropers et al (11) demonstrated feasibility of retrospectively ECG-gated multi–detector row CT angiography for evaluation of coronary artery bypass graft patency and stenosis. Although Ropers et al reported a high diagnostic accuracy, various artifacts prevented a large number of grafts from being evaluated diagnostically.

Among other artifacts, motion-related artifacts are in general a critical issue when using retrospectively ECG-gated multi–detector row CT angiography for evaluation of the coronary arteries. When imaging coronary artery bypass grafts, this is especially true for the distal graft anastomosis, where analysis is often limited even with the high temporal and spatial resolution provided by multi–detector row CT angiography (11). However, our practical experience suggests that the visibility of the individual graft segments may be dependent on the image reconstruction interval of the CT data set.

Thus, the purpose of our study was to evaluate the influence of different reconstruction intervals of retrospectively ECG-gated multi–detector row CT angiography on the image quality of different segments of various types of coronary artery bypass grafts.

MATERIALS AND METHODS

Patients and Grafts

During a 12-month period, 24 consecutive patients with coronary artery bypass grafts who had been referred for conventional coronary angiography for symptom-atic coronary heart disease were considered eligible for this study. Exclusion criteria were the following: history of renal insufficiency (creatinine level, >2.0 mg/dL [177 μmol/L]), history of adverse reactions to iodinated contrast agents (four patients), atrial fibrillation, shortness of breath, and unwillingness to give informed consent for the study protocol (three patients). Presence of implanted pacemakers (one of 20 patients [5%]) or valve prosthesis was not an exclusion criterion.

Hence, the final study group consisted of 20 consecutive patients (17 men with a mean age of 68.9 years and age range of 55–79 years; three women with a mean age of 68.7 years and age range of 63–77 years) with 62 coronary artery bypass grafts. There was no statistically significant difference between men and women with regard to age (Mann-Whitney U test, P = .71). All patients had a sinus rhythm (mean heart rate, 70 beats per minute; range, 34–102 beats per minute). All patients underwent conventional coronary angiography first, followed by multi–detector row CT angiography within 3 days. No coronary intervention was performed during conventional angiography. The study was approved by the local ethics committee, and written informed consent was obtained from all patients. Informed consent also included information about the potential risk of additional radiation with CT angiography.

Twenty-one of 62 (34%) coronary artery bypass grafts were IMA grafts, and 41 of 62 (66%) were venous grafts. Of the 21 IMA grafts, 17 (81%) were left IMA grafts that were grafted onto the left anterior descending artery. Four of 21 (19%) IMA grafts were right IMA grafts that were grafted onto the right coronary artery. Of the 41 venous grafts, 12 (29%) were grafted onto the left circumflex coronary artery, and 15 (36%) were grafted onto the left anterior descending artery. Fourteen of 41 (34%) venous grafts were grafted onto the right coronary artery.

For the purpose of further evaluation, grafts were separated into three types according to the site of the distal anastomosis of the graft on the native coronary artery. Type 1 grafts had distal anastomosis to segments 6–10 (proximal [segment 6], middle [segment 7], and distal [segment 8]) left anterior descending artery, first [segment 9] and second [segment 10] diagonal branch; 32 of 62 bypass grafts (52%). Type 2 grafts had distal anastomosis to segments 11–15 (proximal [segment 11] and distal [segment 13]) left circumflex artery, first marginal branch [segment 12], posterolateral marginal branch [segment 14], and posterior descending branch [segment 15]; 12 of 62 bypass grafts (19%). Type 3 grafts had distal anastomosis to segments 1–4 (proximal [segment 1], middle [segment 2], and distal [segment 3]) right coronary artery and posterior descending branch [segment 4]; 18 of 62 bypass grafts (29%). Segment 5 corresponded to the left main coronary artery. There was no graft on this segment in our study. The time interval between implantation of the peripheral arterial bypass graft and inclusion of the patients into the study ranged between 2 and 20 years (mean, 10 years).

Imaging and Reconstruction Intervals

All CT scans were obtained by using a Somatom Volume Zoom four-channel multi–detector row CT scanner (Siemens, Forchheim, Germany). After an initial anteroposterior scout image was obtained (120 kV, 50 mAs) with the patient in supine position, the scanning range was planned individually for each patient to encompass the extent of both the coronary artery bypass grafts and the coronary arteries, ranging from the subclavian artery (including the proximal segment of IMA grafts) to the apex of the heart. The mean cranio-caudal distance of the volume data set was 17 cm (range, 16–19 cm). All imaging was performed in inspiratory breath hold (21–25 seconds), preceded by mild hyperventilation with oxygen-enriched air (4 L oxygen per minute). Before image acquisition, all patients received 0.8 mg of nitroglycerine sublingually to standardize vasomotor tone in the native coronary arteries beyond the graft anastomosis. A patient’s daily medication was either stopped or changed for the purpose of the study, and additional β-blockers were not administered in preparation for CT scanning.

Contrast material–enhanced multi–detector row CT was performed after administration of 140 mL of a nonionic ioximated contrast medium (iopromidum, Ultravist 300; Schering, Berlin, Germany; 300 mg of iodine per milliliter) via a 20–22-gauge needle, which was placed into a superficial vein located in the antecubital fossa. The contrast medium was administered with an automated injector (Ulrich Medical, Ulm-Jungingen, Germany) at a flow rate of 4 mL/sec, followed by a 50-mL flush of saline at the same flow rate. To achieve optimal contrast enhancement, the scanning delay
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was determined individually for each patient before CT scanning by using a test bolus.

Ten consecutive transverse CT images at the level of the aortic arch were obtained every 2 seconds without table feed, starting 12 seconds after injection of a 20-mL test bolus of iopromidum at a flow rate of 4 mL/sec, followed by a 50-mL saline flush at the same flow rate. The scanning delay was determined as the interval from the start of injection of contrast material to peak enhancement in the aortic arch, plus 3 seconds. Peak enhancement was determined visually by one radiologist (J.K.W., with 3 years of experience in reading cardiac multi-detector row CT angiograms) by evaluating the vascular opacification at the level of the aortic arch. The additional 3-second delay was chosen to ensure passage of the contrast medium into the coronary artery tree and the coronary artery bypass grafts before the onset of scanning (12). The mean delay time between start of injection of contrast material and start of CT scanning was 25 seconds (range, 21–30 seconds).

Contrast-enhanced multi-detector row CT data were collected in helical mode with simultaneous acquisition of four sections with 2.5-mm section thickness, 500-msec rotation time, and table feed of 3.8 mm per rotation (pitch, 0.38). The tube current was 300 mA at 120 kV. A digital ECG file from the patient was recorded simultaneously during multi-detector row CT scanning.

Raw CT data and the digital ECG file were used for retrospective reconstruction of the transverse images by using a commercially available workstation (Volume Zoom Navigator, software release VA20B; Siemens). Depending on the heart rate of the patient, two reconstruction algorithms were used: a conventional single-segmental algorithm for heart rates below 65 beats per minute (one subsegment of consecutive helical data from the same heart cycle was used, resulting in a maximal temporal resolution of 250 msec) and an adaptive two-segmental reconstruction when the heart rate was higher than 65 beats per minute (CT data from two adjacent heart cycles were used for reconstruction with a maximum temporal resolution of 125 msec). In all patients, 10 sets of reconstructions—at 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, and 90% of the R-R interval of the previous R wave—were performed for each raw data set with a B30 kernel (a medium soft-tissue kernel). The reconstructed effective section thickness (full width at half maximum of the helical section sensitivity profile) was 3 mm, and the image increment was 1.5 mm, which resulted in a mean of 1,130 transverse images (range, 1,070–1,270 images). In all patients, the reconstruction field of view was 20 cm with an image matrix of 512 × 512 pixels. This resulted in an interpolated voxel size of 0.4 × 0.4 × 1.5 mm.

CT scans were acquired successfully in all patients without any complications. The imaging protocol was well tolerated by all patients, and all patients were able to hold their breath during CT data acquisition (mean, 22 seconds; range, 21–25 seconds). The mean total room time, defined as the time from patient entry into the CT suite until scanning was finished, was 15 minutes (range, 11–17 minutes) for all patients.

Image Analysis

Imaging data from all patients were transferred to a dedicated workstation (Advantage Windows 4.0; GE Medical Systems, Milwaukee, Wis) equipped with commercially available software. Image analysis was performed separately by two independent blinded radiologists (reader 1, T.B., and reader 2, J.K.W., both with 3 years of experience in reading cardiac multi-detector row CT angiograms) on the basis of transverse CT angiographic images and volume-rendered displays, which were reconstructed by an independent technician who was not involved in the study.

For generation of volume-rendered displays, a technician prepared a model after manual segmentation of obscuring bone structures by using the commercially available software installed on the workstation. The percentage classification transfer function was established individually for the data set of each patient to maximize contrast material-filled vascular structures while eliminating partially enhancing surrounding tissue. The lower threshold of the low-to-high opacity curve was adjusted subjectively to represent the attenuation of the vasculature. This volume-rendered model was available for both readers at the workstation. Therefore, for image analysis, each reader was able to select any possible view at any angle along the z axis of the heart by using the volume-rendered model.

Both readers independently adjusted the optimal window settings for assessment of coronary artery bypass grafts for each patient individually (mean window width, 600 HU; mean center level, 80 HU). A cine mode was available on the workstation for rapid interactive interpretation. Both readers were blinded to patient data, including clinical history and findings from conventional coronary angiography, and to the ECG-gating parameters. The readers analyzed all CT data sets of each patient in random order, but the CT data sets of all 10 reconstruction intervals for each individual patient were available on the workstation for analysis. However, the readers did not know the percentage of the reconstruction interval of each individual patient’s CT data. The number and course of the coronary artery bypass grafts as obtained from surgical reports were known to both readers for each patient.

For the purpose of analysis, each graft was divided into three segments: proximal segment, including the proximal 1-cm length of the graft (including the proximal anastomosis in venous bypass grafts); body of the graft; and distal anastomosis, including the distal 1 cm of the graft. Both readers assessed image quality for each graft segment on each of the 10 reconstructed ECG-gated data sets by using a five-point Likert grading scale: 1, nondiagnostic (diagnostic information not obtained from nonvisible graft segment); 2, poor (severe motion artifacts with doubling and/or blurring of the segment); 3, moderate (moderate motion artifacts with moderate blurring of the segment); 4, good (minor motion artifacts with slight blurring of the segment); and 5, excellent (no motion artifact with clear delineation of the entire segment).

For the assessment of image quality of each segment, scoring was based on the overall impression of all individual sections belonging to each graft segment. For example, a clip artifact present in only one section of a graft segment did not result in an image quality grade 1 if the other sections of the graft segment were of good or excellent image quality. Image quality degradation caused by metal clip artifacts was recorded.

Graft patency was evaluated for each of the three segments by both readers independently. For this purpose, the reconstruction data set with the best subjective image quality according to the reader was used for further evaluation. Patency or occlusion of the grafts was assessed for all three segments subjectively. An electronic caliper was not used for quantification of the luminal diameter. In addition, in patent graft segments, the presence or absence of hemodynamically significant ste-
nosis (50%–99% luminal narrowing) was assessed for all three segments.

**Conventional Coronary Angiography**

Biplanar conventional coronary angiography was performed by using the Seldinger technique via the femoral artery with a 6- or 7-F catheter. To standardize vasomotor tone in the native coronary arteries beyond the graft anastomosis, all grafts were visualized selectively after injection of a 0.1-mg bolus of nitroglycerine within the graft lumen. Aortography and ventriculography were performed before selective catheterization of the coronary arteries and the grafts or graft stumps according to the surgical reports. Visualization of the coronary arteries and the grafts was performed according to standard projections (six projections for the left coronary artery, four projections for the right coronary artery, and an additional two to four projections for each graft).

All studies were documented on videotape for subsequent review. Angiograms were interpreted independently by one radiologist (R.K., 3 years of experience), who had performed the angiography.

The cardiologist was aware of the number of grafts and locations of the graft bodies as obtained from surgical reports. The cardiologist was asked to report patency or occlusion of each segment of the grafts individually. Presence of luminal stenosis of each segment was also noted by using the same grading scale as that used for CT angiograms. An electronic caliper was not used for quantification of luminal diameter.

**TABLE 1**

<table>
<thead>
<tr>
<th>Graft Segment</th>
<th>0% of Cardiac Cycle</th>
<th>10% of Cardiac Cycle</th>
<th>20% of Cardiac Cycle</th>
<th>30% of Cardiac Cycle</th>
<th>40% of Cardiac Cycle</th>
<th>50% of Cardiac Cycle</th>
<th>60% of Cardiac Cycle</th>
<th>70% of Cardiac Cycle</th>
<th>80% of Cardiac Cycle</th>
<th>90% of Cardiac Cycle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proximal segment*</td>
<td>4.44 ± 0.72</td>
<td>4.58 ± 0.61</td>
<td>4.38 ± 0.63</td>
<td>4.52 ± 0.7</td>
<td>4.53 ± 0.64</td>
<td>4.64 ± 0.53</td>
<td>4.64 ± 0.53</td>
<td>4.46 ± 0.66</td>
<td>4.49 ± 0.65</td>
<td></td>
</tr>
<tr>
<td>Body of graft</td>
<td>3.56 ± 0.75</td>
<td>3.5 ± 0.81</td>
<td>3.77 ± 0.69</td>
<td>3.87 ± 0.71</td>
<td>3.98 ± 0.67</td>
<td>4.12 ± 0.68</td>
<td>4.08 ± 0.6</td>
<td>4.06 ± 0.63</td>
<td>3.92 ± 0.63</td>
<td>3.85 ± 0.76</td>
</tr>
<tr>
<td>Distal anastomosis†</td>
<td>3.46 ± 1.04</td>
<td>3.63 ± 0.99</td>
<td>3.95 ± 0.95</td>
<td>3.96 ± 0.97</td>
<td>3.89 ± 0.89</td>
<td>4.11 ± 0.96</td>
<td>4.22 ± 0.84</td>
<td>4.25 ± 0.86</td>
<td>3.87 ± 0.9</td>
<td>3.73 ± 0.94</td>
</tr>
</tbody>
</table>

Note.—Data are mean image quality ± SD.

* Proximal 1-cm graft length (including proximal anastomosis in venous bypass grafts).

† Includes distal 1 cm of graft segment.

**Figure 1.** Graphs demonstrate mean image quality of (a) proximal segment, (b) graft body, and (c) distal anastomosis of all graft types as assessed by both readers on CT angiograms. Error bars indicate 1 standard error. Image quality was not significantly different for various reconstruction intervals in a (P > .8) but was significantly different for various reconstruction intervals in b and c (P < .001 for both).
Radiation Dose Estimation

One physicist (F.R.V., 10 years of experience) calculated effective radiation dose delivered during CT angiography for a mean distance of 17 cm (the mean craniocaudal distance of the volume data set) for both men and women. The dose length product was calculated by using a normalized weighted CT dose index value of 0.10 mGy/cm. This value is representative of the normalized weighted CT dose index expected with the type of multi-detector row CT scanner used at 120 kV in this study. The dose length product was then converted into effective dose values by means of a conversion factor of 0.017 mSv/mGy · cm according to the Commission of the European Communities guidelines on quality criteria for CT (13). All dose calculations were performed by a physicist.

Estimates of the effective dose of coronary angiography were calculated by one physicist on the basis of dose area product quantity that corresponded to the acquisition protocol used. The dose area product is displayed by the digital subtraction angiography system itself and is representative of the total energy deposited in the examined volume. The dose area product value displayed by the unit was verified according to the method described by Bochud et al (14). A conversion factor of 0.10 mSv/Gy · cm was used for both men and women according to the conversion factors published by Le Heron (15) for lateral and posteroanterior exposures in the chest area.

Statistical Analysis

Means and SDs of the grading of image quality were calculated for each of the three segments for all three types of grafts. Image quality differences between the three segments and between the three types of grafts were compared by using repeated-measures analysis of variance. In addition, analysis of variance was used to evaluate differences between IMA and venous grafts with regard to image quality of the three graft segments.

Sensitivities, specificities, positive and negative predictive values, and accuracies of CT angiography compared with conventional angiography for determination of graft stenosis were calculated, as well as 95% CIs based on binominal probabilities for both readers. If there was no hemodynamically significant stenosis in the study group, then sensitivities, specificities, positive and negative predictive values, and accuracies could be calculated only with regard to detection of graft patency versus occlusion. Interobserver agreements between both readers who evaluated multi-detector row CT angiograms were calculated by using κ statistics (including 95% CIs) with regard to determination of bypass graft patency versus occlusion. According to Landis and Koch (16), a κ value of 0 indicated poor agreement; 0.01–0.20, slight agreement; 0.21–0.40, fair agreement; 0.41–0.60, moderate agreement; 0.61–0.80, good agreement; and 0.81–1.00, excellent agreement.

RESULTS

Quality of CT Angiograms

When all segments of all types of coronary artery bypass grafts were analyzed together, the reconstruction interval significantly influenced image quality, as rated by both readers (P < .001). On average, all graft segments were best visualized at early and middiastole (50%–70% of the cardiac cycle). At 50% of the cardiac cycle, mean image quality was 4.18 ± 0.80 for reader 1 and 4.21 ± 0.83 for reader 2. At 60% of the cardiac cycle, mean image quality was 4.30 ± 0.76 for reader 1 and 4.37 ± 0.76 for reader 2. At 70% of the cardiac cycle, mean image quality was 4.30 ± 0.74 for reader 1 and 4.33 ± 0.73 for reader 2. The lowest scores of image quality were rated at 0% of the cardiac cycle by both readers (mean image quality, 3.81 ± 0.96 for reader 1 and 3.83 ± 0.96 for reader 2).

Table 1 summarizes mean image quality of the three segments of all graft types as assessed by both readers.

Image quality was different for all three graft segments. For the proximal segment, there was no statistically significant difference in image quality between the images reconstructed at the 10 different reconstruction intervals (P = .8; Figs 1, 2) for both readers and for all three graft types. In contrast, image quality of the body of the graft (Fig 1) and image quality of the distal anastomosis (Fig 1) for all three graft types changed significantly with varying reconstruction intervals for both readers (P < .001; Fig 2).

Independent of graft type, the best image quality of the graft body and the distal anastomosis was obtained by both readers at a reconstruction interval between 50% and 70% of the cardiac cycle (Fig 1, Fig 3). There was no statistically significant difference between reader 1 and reader 2 with regard to grading of image quality of all segments of all three grafts.
Figure 3. Graph demonstrates mean image quality of the graft body in the evaluation of three types of coronary artery bypass grafts. Image quality was dependent on reconstruction interval for multi-detector row CT angiograms read by both readers. Type 1 (○), distal anastomosis to segments 6–10 (left anterior descending artery); type 2 (△), distal anastomosis to segments 11–15 (left circumflex artery); and type 3 (▲), distal anastomosis to segments 1–4 (right coronary artery). Error bars indicate ±1 standard error. Best image quality of the graft body was obtained at 60% of the cardiac cycle for type 1 grafts, at 70% for type 2 grafts, and at 50% for type 3 grafts.

Figure 4. Graph demonstrates mean image quality of distal anastomosis in the evaluation of three types of coronary artery bypass grafts. Image quality was dependent on reconstruction interval for multi-detector row CT angiograms read by both readers. Type 1 (○), distal anastomosis to segments 6–10 (left anterior descending artery); type 2 (△), distal anastomosis to segments 11–15 (left circumflex artery); and type 3 (▲), distal anastomosis to segments 1–4 (right coronary artery). Error bars indicate ±1 standard error. Best image quality of distal anastomosis was obtained at 60% of the cardiac cycle for type 1 grafts, at 70% for type 2 grafts, and at 50% for type 3 grafts.

Figure 5. Transverse multi-detector row CT angiographic source images (window width, 600 HU; center level, 80 HU) obtained at the level of the distal anastomosis (arrow) of a venous bypass graft (BP) grafted onto the distal right coronary artery (RCA) (type 3) in a 66-year-old woman. Source images were reconstructed at (a) 20%, (b) 50%, and (c) 70% of the cardiac cycle. At 50%, both readers rated image quality of the distal anastomosis as excellent (grade 5). Note that surgical clip (arrowhead) at the distal anastomosis can be depicted. Both readers rated image quality of the distal anastomosis as good (grade 4) at 70% and moderate (grade 3) at 20% of the cardiac cycle.
types ($P = .95$). In addition, there was no significant difference between IMA and venous grafts with regard to image quality of the proximal segment ($P = .16$), the graft body ($P = .31$), and the distal anastomosis ($P = .34$).

When conducting a subanalysis with regard to image quality according to graft type, both the graft body (Fig 3) and the distal anastomosis (Fig 4) of type 3 grafts (distal anastomosis to segments 1–4) were best visualized at a reconstruction interval of 50% of the cardiac cycle (Fig 5). The reconstruction interval that resulted in the best overall image quality for both the graft body and the distal anastomosis of type 1 grafts (anastomosis to segments 6–10) was 60% of the cardiac cycle (Fig 6). The graft body and the distal anastomosis of type 2 grafts (anastomosis to segments 11–15) were best visualized overall at a reconstruction interval of 70% of the cardiac cycle.

### Assessment of Graft Patency

Table 2 demonstrates the breakdown of CT and conventional angiographic findings by both readers with regard to grading of graft stenosis or occlusion. On CT angiograms, reader 1 identified occlusion (grade 3) in 36 of 186 (19%) segments, and reader 2 detected occlusion in 33 of 186 (18%) segments. Hemodynamically significant stenosis (grade 2) was diagnosed in none of the segments by both readers. The interobserver agreement between both readers was excellent ($k = 0.84$; 95% CI: 0.78, 0.89).

Conventional angiographic findings indicated occlusion (grade 3) in 36 of 186 (19%) segments. Similar to CT angiographic findings, no grade 2 luminal stenosis was present in the coronary artery on the basis of evaluation of conventional angiograms. For the assessment of patency, when CT angiograms and conventional angiograms were compared, reader 1 findings agreed in 174 of 186 (94%) segments, and reader 2 findings agreed in 177 of 186 (95%) segments (Fig 7).

Table 3 summarizes true-positive findings, true-negative findings, false-positive findings, false-negative findings, sensitivities, specificities, and accuracies of CT angiography for assessment of graft patency for both readers. Since no hemodynamically significant stenosis was identified at evaluation of CT data sets or at analysis of conventional angiograms, diagnostic performance was calculated only with regard to graft patency. Sensitivity and specificity values of CT angiography for detection of graft patency were 83% and 96%, respectively, for reader 1 and 83% and 98%, respectively, for reader 2. The accuracy of CT angiography in the detection of graft patency was 94% for reader 1 and 95% for reader 2.

Assessment of bypass graft patency was hampered because of metal clip artifacts in five of 62 (8%) grafts in five of 20 (25%) patients. Artifacts from metal clips were present at the distal anastomosis of three left IMA grafts, at the proximal segment of one left IMA graft, and at the distal anastomosis of one venous bypass graft that was grafted onto the left anterior descending coronary artery. However, image analysis was still possible for diagnostic purposes with regard to assessment of graft patency.

### Radiation Exposure

With the use of the CT parameters described, the effective dose of the multidetector row CT angiograms was calculated to be 11.4 mSv for both men and women. For conventional coronary angiography, the mean effective dose was estimated to be 2.1 mSv (range, 1.1–3.3 mSv) for both men and women.

### DISCUSSION

So far, conventional coronary angiography has been considered the imaging modality of choice for the assessment of coronary artery bypass grafts in patients with symptomatic coronary artery disease after bypass graft placement. Since conventional coronary angiography is an invasive procedure that includes a considerable risk of complications and requires hospitalization, alternative noninvasive diagnostic modalities have been developed for evaluation of coronary artery bypass grafts.

Contrast-enhanced three-dimensional magnetic resonance (MR) angiography is a promising technique that allows both assessment of coronary artery bypass graft occlusion and graft stenosis with a diagnostic accuracy of up to 83% (17). Limited spatial resolution and artifacts caused by vascular clips surrounding arterial grafts may limit MR angiography in the evaluation of small arterial bypass grafts, such as IMA bypass grafts (17). In addition, MR angiography cannot be performed in claustrophobic patients or in patients with cardiac pacemakers or defibrillators, which are often implanted in patients with coronary artery disease.

Electron-beam CT has been demonstrated to be useful for evaluation of coronary artery bypass grafts, with a reported diagnostic accuracy of 97%–100% for detection of graft patency (18,19). However, possible drawbacks of electron-beam CT include the limited volume coverage (maximum 40 sections acquired...
with a section thickness of 3 mm, resulting in a maximal craniocaudal volume coverage of 12 cm) and the fact that CT data can only be acquired with prospective ECG gating (20).

Ropers et al (11) reported their experience in the assessment of coronary artery bypass grafts by using retrospectively ECG-gated multi–detector row CT angiography. In that prospective study, the authors evaluated 65 patients with a total of 182 bypass grafts with conventional coronary angiography as the standard of reference. According to the findings of Ropers et al (11), retrospectively ECG-gated multi–detector row CT angiography yielded an excellent diagnostic performance with regard to assessment of occlusion of the graft (sensitivity, 97%; specificity, 98%) and a satisfactory diagnostic performance with regard to assessment of stenosis of the bypass graft (sensitivity, 75%; specificity, 92%). However, a major drawback of the study was the fact that 47 of 124 (38%) of the patent grafts were not eligible for analysis of presence or absence of high-grade stenosis (11). Although metal artifacts were the most frequent cause of grafts that could not be evaluated (17 of 48), a substantial number of the nonanalyzable coronary bypass grafts resulted from motion artifacts related to the heart, breathing, or movement (11). The thicker sections used in our study and, hence, the shorter time for inspiratory breath holding, as well as optimal determination of the reconstruction interval, may have reduced the number of nonanalyzable graft segments in our study. Image quality was reduced because of the presence of metal clip artifacts in five of 62 (8%) coronary artery bypass grafts in five of 20 (25%) patients in our study. The lower frequency of clip artifacts in our study might have also been influenced by different surgical techniques.

According to articles published previously and our own experience, image quality of different parts of the coronary artery bypass graft is usually not uniform (12,20). Since the proximal segment is rarely affected by heartbeat-related artifacts, the body and in particular the distal anastomosis of the bypass graft are susceptible to these artifacts. In the study of Ropers et al (11), out of nine false-pos-
The diagnostic performance of CT angiography in the detection of graft patency in 20 patients with 62 grafts is shown in Table 3. The table includes the number of true-negative findings, false-negative findings, true-positive findings, and false-positive findings for each segment of the graft. The sensitivity, specificity, positive predictive value, and negative predictive value are also listed for each reader.

The results of the study indicate that delineation of the body and the distal anastomosis of the graft may be improved by optimally selecting the reconstruction interval within the cardiac cycle. The body and distal anastomosis of coronary artery bypass grafts that were grafted onto the left anterior descending artery (type 1) as well as onto the left circumflex artery (type 2) were best visualized with reconstruction intervals at 60%–70% of the cardiac cycle. For coronary artery bypass grafts that were grafted onto the right coronary artery (type 3), image quality of the body and distal anastomosis of the graft was significantly improved by selecting the reconstruction interval at 50% of the cardiac cycle.

The influence of the reconstruction interval on graft visibility is in accordance with the findings of two studies (12, 20) in which the influence of the reconstruction interval on retrospectively ECG-gated multi–detector row CT angiography on the visibility of coronary arteries was investigated. By using retrospectively ECG-gated multi–detector row CT angiography, Kopp et al (20) showed that the left anterior descending artery was best visualized in mid-diastole at 60%–70% of the cardiac cycle. In addition, the same authors demonstrated that the left circumflex artery is best visualized at 50% of the cardiac cycle, and the right coronary artery is best visualized at 40% of the cardiac cycle. Similar results were also reported by Hong et al (12), who achieved optimal image quality for the right coronary artery when the images were reconstructed at 50% of the cardiac cycle and when the left circumflex coronary artery was reconstructed at 60% of the cardiac cycle. In the same study, Hong et al (12) showed that optimal image quality for the left anterior descending coronary artery was obtained equally at 50% and 60% of the cardiac cycle. Hence, according to the results of the aforementioned studies and the results of our study, it may be concluded that the image reconstruction interval for retrospectively ECG-gated multi–detector row CT angiography should be adapted for evaluation of the graft body and the distal anastomosis of the graft to improve image quality.

The fact that the image quality of the proximal segment of the coronary artery bypass graft was independent of the reconstruction interval may be explained by the anatomic relationship of the anastomosis relative to the aortic level. In our series, the proximal segment originated from either the ascending aorta (in venous bypass grafts) or the subclavian artery (in IMA bypass grafts). Since it has been demonstrated that for retrospectively ECG-gated multi–detector row CT angiography, heartbeat-related motion artifacts of the thoracic aorta were less pronounced when moving from the level of the aortic valve to the ascending aorta and supraaortic vessels (21), this may explain why the reconstruction interval did not influence the image quality of the proximal segment.

When compared with the results in the study of Ropers et al (11), the sensitivity and specificity of multi–detector row CT angiography with regard to assessment of graft patency obtained in our study were lower (83% sensitivity for both readers in our study vs 97% in the study of Ropers et al; 96% specificity for reader 1 and 98% for reader 2 in our study vs 98% in the study of Ropers et al). The lower sensitivity and specificity values obtained in our study may be explained by the fact that the analysis performed in our study was based on different bypass graft segments instead of the entire graft, as used in the study of Ropers et al (11). In addition, in the study of Ropers et al, a section thickness of 1.25 mm was used, whereas a section thickness of 2.5 mm was used in our study. In our study, however, diagnostic accuracy with regard to assessment of graft patency was similar to that in the study of Ropers et al for both readers (94% for reader 1 and 95% for reader 2 in our study vs 98% in the study of Ropers et al).

A major drawback of retrospectively ECG-gated multi–detector row CT data acquisition is the radiation dose. Since the data are acquired with an overlapping helical pitch and continuous x-ray exposure, the applied radiation dose is higher than that in the prospectively ECG-triggered sequential acquisition. In our study, a mean effective dose value of 11.4 mSv was calculated. When compared with the mean effective dose values calculated for conventional coronary angiography, the mean effective dose with multi–detector row CT angiography was higher by a factor of about five. However, by reducing the tube output during heart phases that are not likely to be targeted by the ECG-gated reconstruction (ie, reconstruction intervals except 50%–70%), a dose reduction of up to 48% is possible (22). To have consistent data acquisition in our study, we did not vary...
the tube output at the different phases of the cardiac cycle. Furthermore, improvements in dose usage of recent-generation 16-channel multi-detector row CT scanners may also help in reducing radiation dose (23).

Flohr et al (23) demonstrated that the relative dose usage can be increased from 70% to 89% when using a 16-channel CT scanner as opposed to a four-channel CT scanner. Since our study has demonstrated that optimal image quality can be obtained at reconstruction intervals between 50% and 70% of the cardiac cycle, our current protocol for assessment of bypass grafts includes dose reduction strategies that reduce the CT tube output during heart phases that are not targeted by the reconstruction intervals. However, if the clinicians ask for additional functional information (eg, assessment of the ejection fraction), reconstruction at 10% increments is still needed, and dose reduction during systole may not be applied. Further studies are warranted to demonstrate whether multi-detector row CT may also provide accurate functional data even with the use of dose reduction strategies.

Several limitations of our study need to be addressed. First, the number of patients was relatively small. Because more than one graft was implanted in most patients, the P values in the analysis of the image quality of the grafts may have been biased as a result of a clustering effect. Since there were no stenotic graft segments in our study population, we could only calculate sensitivity and specificity of retrospectively ECG-gated multi-detector row CT angiography with regard to diagnosis of graft patency versus occlusion but not with regard to graft stenosis.

The lack of hemodynamically significant stenosis in this series may be explained by the fact that the frequency of graft stenosis is reported to be significantly lower than that of occlusion (24). We did not evaluate systematically the stepwise improvement of the diagnostic confidence of the readers when analyzing different reconstruction intervals. In addition, the interval of 10% for image reconstruction was chosen arbitrarily in our study. Finally, we did not assess the influence of the patient’s heart rate on image quality. A recent study (25) demonstrated that better image quality of coronary arteries may be obtained in patients with heart rates below 70 beats per minute. Future studies are warranted to evaluate whether heart rate may also influence image quality of different segments of various types of coronary artery bypass grafts.

In conclusion, our study has demonstrated that appropriate selection of reconstruction interval in retrospectively ECG-gated multi-detector row CT angiography can significantly improve the image quality of different types of coronary artery bypass grafts, the body of the graft, and the distal anastomosis in particular. With optimized retrospective reconstruction, patency of the coronary artery bypass graft can be predicted with high accuracy.

References