Diagnostic Accuracy of Noninvasive Coronary Angiography in Patients After Bypass Surgery Using 64-Slice Spiral Computed Tomography With 330-ms Gantry Rotation

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Background—Multidetector computed tomographic angiography (MDCT) has been shown to allow detection of coronary artery bypass graft (CABG) occlusions and stenoses. However, the assessment of native coronary arteries in addition to CABG has thus far not been sufficiently validated.

Methods and Results—Fifty patients with a total of 138 CABG (34 mammary grafts, 3 radial grafts, 101 venous grafts) were investigated by MDCT (0.6-mm collimation, 32 detector rows, 2 focal points, 330-ms rotation) 9 to 252 months (mean, 106 months) after surgery. CABG and all native coronary arteries with a diameter of >1.5 mm were evaluated for the presence of significant stenoses (≥50% diameter reduction). Results were compared with quantitative coronary angiography. By MDCT, all CABG were evaluable and were correctly classified as occluded (n=38) or patent (n=100). Sensitivity for stenosis detection in patent grafts was 100% (16/16) with a specificity of 94% (79/84). For the per-segment evaluation of native coronary arteries and distal runoff vessels, sensitivity in evaluable segments (91%) was 86% (87/101) with a specificity of 76% (354/465). If evaluation was restricted to nongrafted arteries and distal runoff vessels, sensitivity was 86% (38/44) with a specificity of 90% (302/334). On a per-patient basis, classifying patients with at least 1 detected stenosis in a CABG, a distal runoff vessel, or a nongrafted artery or with at least 1 unevaluable segment as “positive,” MDCT yielded a sensitivity of 97% (35/36) and specificity of 86% (12/14).

Conclusions—We found that 64-slice MDCT permits the evaluation of bypass grafts and the assessment of the native coronary arteries for the presence of stenosis. (Circulation. 2006;114:).

Key Words: angiography ■ bypass ■ computed tomography ■ imaging ■ tomography

Multidetector computed tomography (MDCT) can be used to visualize the lumen of coronary artery bypass grafts after intravenous injection of contrast agent. Initial studies using 4-slice spiral MDCT and ECG-gated retrospective reconstruction revealed promising results regarding the assessment of significant bypass stenoses. However, because of artifacts caused by cardiac motion as well as metal clips and poor opacification, a significant number of grafts (up to 38%) were unevaluable for the presence or absence of high-grade disease. The introduction of 16-slice technology reduced the number of unevaluable bypass grafts, whereas diagnostic accuracy for the detection of graft stenosis increased. However, the evaluation of the distal anastomosis site in particular remained challenging. In addition, evaluation of the native coronary arteries and distal runoff vessels was difficult because of the often advanced coronary disease and pronounced coronary calcification observed in patients after bypass surgery. Only 2 studies, 1 using 4-slice CT and

Clinical Perspective p 0000

1 with 16-slice technology, attempted detection of stenoses not only in bypass grafts but also in the runoff and nongrafted arteries. In those studies, sensitivities between 83% and 90% and specificities between 59% and 75% for the detection of significant lesions in the native coronary arteries were reported. Clinically, the mere assessment of bypass grafts will usually not be sufficient in patients who develop symptoms and ischemia after bypass surgery. New lesions in the coronary arteries are a potential culprit and must be detectable for computed tomography (CT) imaging to play a significant role in the workup of such patients. With the improved spatial and temporal resolution of 64-slice multidetector spiral CT, assessment of the distal anastomosis site, as well as evaluation of severely calcified coronary arteries, should be possible with greater accuracy. Initial studies of 64-slice CT in the assessment of patients with suspected
coronary artery disease have demonstrated increased accuracy and higher evaluability rates compared with previous scanner generations. One previously published study reported initial experiences with 64-slice CT for the noninvasive visualization of bypass grafts. Image quality was reported as “diagnostic” in 94% (48/51) of the grafts. When unevaluable grafts (n=3) were classified as stenotic, a sensitivity of 98% and specificity of 89% were found for the detection of graft stenosis and occlusion. However, the study was limited to the evaluation of bypass grafts. Native coronary arteries and the distal runoff vessels were not included in the analysis.

In this study, the accuracy of 64-slice MDCT coronary angiography for the evaluation of patients after coronary artery bypass surgery was assessed. Bypass grafts, distal anastomosis sites, and the native coronary artery system were included in the analysis. Results were compared with invasive quantitative coronary angiography.

Methods

Patients

Fifty consecutive patients with previous coronary artery bypass surgery (38 men, 12 women; mean age, 67 years; age range, 44 to 82 years; mean weight, 82 kg, weight range, 64 to 107 kg) with a total of 138 grafts (1 to 5 grafts per patient; average, 2.8) who had been referred for invasive coronary angiography for clinical reasons were investigated 9 to 252 months (mean, 106 months) after bypass operation. In all patients, progression of coronary artery disease was suspected because of either new onset of typical chest pain (n=29), a positive stress test (n=1), or both (n=10). Of the 138 bypass vessels, 100 were venous grafts (with 110 distal graft anastomoses), 32 were left internal mammary grafts (27 to the left anterior descending coronary artery and 5 to the first diagonal branch), 2 were right internal mammary artery grafts (both used as free arterial grafts to the left anterior descending coronary artery), and 4 were radial artery grafts used as free transplants to the left anterior descending coronary artery. Only patients in stable clinical condition, in sinus rhythm, without implanted pacemakers or valve prostheses, and without contraindications to the administration of iodinated contrast agent were included in the study. Patients with a possible pregnancy, an acute coronary syndrome, or stents in native coronary arteries or bypass grafts were excluded. Forty-two patients (84%) were on long-term medication with β-blockers. Invasive angiography was performed independently of the MDCT results in all patients within 3 days after MDCT. All patients gave written informed consent, and the protocol was approved by the institutional review board.

MDCT Protocol

Patients with a heart rate of >60 bpm received 100 mg atenolol (Tenormin, AstraZeneca, Wedel, Germany) orally 1 hour before the scan. If the heart rate was still >60 bpm at the time of the MDCT investigation, up to 4 doses of 5 mg metoprolol (Beloc, AstraZeneca, Wedel, Germany) were administrated intravenously to lower the heart rate to ≤60 bpm. In addition, all patients received 0.8 mg isosorbide dinitrate sublingually immediately before MDCT scanning. MDCT was performed with the use of a SOMATOM Sensation 64 Cardiac CT scanner (Siemens Medical Solutions, Forchheim, Germany). The number, type, and location of the bypass grafts were known by the operators of the CT scanner. First, a noncontrast posteroanterior projectional image of the chest was acquired to determine the position of the heart and aortic arch and to define the scan volume for further imaging. Then the contrast agent transit time was determined with a bolus injection of 10 mL contrast agent, followed by 50 mL saline solution, as previously described. To reduce radiation dose, and similar to previous studies, the origin and very proximal part of the internal mammary artery grafts were not covered by the scan volume. Instead, the upper level was set at the midlevel of the aortic arch. For acquisition of the volume data set, the patients received a total of 80 mL of contrast agent (Omnipaque370, Schering, Berlin, Germany) at a rate of 5 mL/s followed by 50 mL saline solution (also at 5 mL/s). Scan parameters for the volume data set were as follows: simultaneous acquisition of 64 slices per rotation with a slice thickness of 0.6 mm, rotation time 330 ms, table feed 3.8 mm per rotation, tube voltage 120 kV, and tube current 750 mA. ECG-gated tube current modulation was used in all patients. It limits the full tube current to a time period of 450 ms in diastole and thus leads to a reduction of the radiation dose of ~50%. Radiation dose was estimated with the use of a PC-based simulation program (ImpactDose version 1.16, Scanditronix Wellhöver, Schwarzenbruck, Germany). It was determined that the average effective dose was 8.55 mSv for men (range, 7.21 to 10.05 mSv) and 12.24 mSv for women (range, 10.4 to 14.8 mSv).

Image Reconstruction

Retrospectively ECG-correlated image reconstruction was performed with the use of a half-scan reconstruction algorithm that provided a temporal resolution of 165 ms in the center of the scan field. Overlapping axial cross-sectional images with 0.75-mm slice thickness were reconstructed with an increment of 0.5 mm with a medium-short convolution kernel (B25f) and an image matrix of 512×512 pixels. The first reconstruction was performed with the reconstruction window starting at 70% of the R-peak-to-R-peak interval. If motion artifacts were present, additional reconstructions in 5% increments and decrements of the R-R interval were performed, as described earlier.

Data Analysis

Quantitative Coronary Angiography

Arterial catheterization and selective conventional angiography of the coronary arteries and bypass grafts, which constituted the standard of reference to validate MDCT, were performed 1 to 3 days after the MDCT procedure. Standard projections were obtained after intracoronary injection of 0.2 mg isosorbide dinitrate and evaluated offline by an independent observer using quantitative coronary angiography software (QuantCor/QCA, PiMedical Imaging, Netherlands). The proximal luminal diameter of all coronary segments and bypass grafts was measured. Segments or grafts with a diameter <1.5 mm were excluded from analysis. In segments with a diameter ≥1.5 mm, lesions with a lumen reduction of ≥50% were considered to represent significant stenoses. The diameter stenosis was deter-
Figure 1. MDCT and invasive coronary angiography in a patient with bypass grafts to the left anterior descending coronary artery and diagonal branch. A, Curved multiplanar reconstructions of the venous bypass graft to the left anterior descending coronary artery. Arrows indicate the bypass grafts, arrowheads the native coronary artery. B, Corresponding invasive angiogram. Arrows indicate the bypass grafts, arrowheads the native coronary artery. C, Curved multiplanar reconstructions of the venous bypass graft to the first diagonal branch. Arrows indicate the bypass grafts, arrowheads the native coronary artery. D, Corresponding invasive angiogram of the venous bypass graft to the first diagonal branch. Arrows indicate the bypass grafts, arrowheads the native coronary artery. E, The 3-dimensional, volume rendering reconstruction demonstrates normal venous bypass grafts: Arrows indicate the bypass grafts, arrowheads the native coronary artery (white, graft to the left anterior descending coronary artery; black, graft to the first diagonal branch). F, Same patient. Curved maximum-intensity projection (5-mm slice thickness) of the right coronary artery demonstrates a significant eccentric stenosis (arrow) in the mid section. G, Invasive coronary angiography of the right coronary artery confirms the MDCT finding (arrow, 73% diameter reduction in quantitative coronary angiography). Ao indicates ascending aorta; LV, left ventricle; RV, right ventricle; and PA, pulmonary artery.
mined by averaging the luminal narrowing from 2 orthogonal projections.

Statistical Analysis
For the determination of the necessary patient number, the 2-sample proportion test was used. Under the assumption of a sensitivity of 90% for contrast-enhanced, 64-slice MDCT to detect a stenosis of >50% lumen reduction on a per-patient basis,13–17 a sample size estimate was performed. Under the assumption that 70% of all patients would have at least 1 coronary stenosis in invasive coronary angiography (the reference standard), it was determined that to estimate a true sensitivity of MDCT of ≥90% (within 8% of the true value for the detection of patients with at least 1 stenosis), a sample size of ≈50 patients would be necessary.

Diagnostic accuracy for the detection of significant lesions by MDCT in comparison to quantitative coronary angiography was expressed as sensitivity, specificity, positive predictive value, and negative predictive value. Calculations were performed for the bypass grafts, for the native coronary arteries, and for the combination of nongrafted arteries and the distal runoff vessels on a per-segment and per-vessel basis. In these analyses, segments and vessels classified as unevaluable were excluded.

In addition, per-patient analyses were performed for bypass grafts, for the combination of nongrafted arteries and the distal runoff vessels, and for any significant stenosis in the bypass grafts and the nongrafted arteries/distal runoff vessels. In these analyses, patients with a detectable stenosis in the bypass grafts or the native coronary arteries, as well as patients with at least 1 unevaluable coronary segment, were classified as “positive” (because the presence of a stenosis could not be ruled out and invasive angiography would be the clinical consequence). Patients in whom all grafts and all coronary segments were evaluable and no significant stenosis was present were classified as “negative.” Data analysis was performed with the software SPSS 11.0 (SPSS Inc, Chicago, Ill).

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

Results
MDCT was performed without complications in all patients. Additional β-blockers were administrated to lower the heart rate in 29 of 50 patients (58%), and the resulting mean heart rate during the scan was 59±9 bpm. Depending on the covered volume (mean, 161±14 mm), breathhold time was between 11.5 and 16.8 seconds (mean, 13.5 seconds). In 33 patients, MDCT data sets free of visible motion artifact were obtained at 70% of the cardiac cycle; whereas in 17 patients, additional reconstructions at different time instants were performed. No patient was excluded from analysis because of a technically inadequate scan or because of insufficient opacification of distal native vessels.

Bypass Grafts
Invasive coronary angiography demonstrated that 100 of 138 bypass grafts were patent and 38 were occluded. Of the patent grafts, 16 had a significant stenosis. In MDCT, all 138 bypass grafts could be evaluated for patency and occlusion, and all were classified correctly as occluded (n=38) or patent (n=100). All 100 grafts that were classified as patent could be evaluated for the presence of stenoses (50% to 99% diameter reduction). In these 100 grafts, all 16 stenoses were correctly identified by MDCT (sensitivity 100%). Nine of the stenoses were located in the body of the bypass grafts, and 7 stenoses were located at the distal anastomotic site (Figures 2 and 3). In 79 of 84 bypass grafts, stenoses were correctly ruled out, whereas in 5 cases, the presence of a significant lesion was incorrectly suspected on the basis of MDCT (specificity 94%). In 4 of these cases, the false-positive lesion was located at the distal anastomosis (1 internal mammary artery graft to the left anterior descending coronary artery and

Figure 2. Venous bypass graft to the right coronary artery 7 years after surgery. A, Curved multiplanar reconstruction demonstrates stenoses in the proximal part of the bypass graft (arrows). B, Invasive angiography confirms the MDCT findings (arrows).
3 venous grafts to the circumflex coronary artery, the first obtuse marginal branch, and the distal right coronary artery, respectively. The remaining false-positive lesion was located in a proximal part of a venous bypass graft to the circumflex coronary artery, and the diameter reduction in quantitative coronary angiography was 28%. Thus, for the detection of significant bypass graft lesions (stenosis or occlusions), a sensitivity of 100% (54/54), specificity of 94% (79/84), negative predictive value of 100% (79/79), and positive predictive value of 92% (54/59) were found.

Coronary Arteries
For the evaluation of native coronary arteries and distal runoff vessels, analysis was performed on a per-segment basis. Of a total of 800 coronary segments in 50 patients, 135 segments with a diameter <1.5 mm on quantitative coronary angiography and 44 vessel segments distal of 19 total occlusions were excluded from analysis. Thus, 621 coronary segments remained in the analysis. Of these 621 segments, invasive angiography, the standard of reference, classified 111 as having significant stenosis and 510 as being free of stenosis. By MDCT, 55 segments (9%) were classified as unevaluable because of degraded image quality. The reasons were presence of severe calcifications in 41 cases and motion artifacts in 14 cases. In evaluable segments, sensitivity for the

Figure 3. Venous bypass graft to the right coronary artery 4 years after bypass surgery. A, Curved multiplanar reconstruction demonstrates a subtotal stenosis at the distal anastomosis site (arrow). B, Invasive angiography confirms the MDCT findings (arrow).

Figure 4. Stenosis of the right posterolateral branch distal to the anastomosis of a venous bypass graft. A, A maximum-intensity projection (5-mm slice thickness) visualizes the distal section of the bypass grafts and anastomosis (arrowhead) to the posterior descending coronary artery (anastomosis). There is retrograde filling of the right posterolateral branch, which has a high-grade, severely calcified stenosis (arrow). B, Invasive angiography confirms the MDCT findings. The arrowhead indicates the anastomosis, the arrow the stenosis in the posterior descending coronary artery.
detected significant stenoses was 86% (87/101) with a specificity of 76% (354/465). When unevaluable segments were classified as positive, overall diagnostic accuracy was 73% (451/621) because invasive angiography demonstrated significant stenoses in 10 of 55 unevaluable segments. If the evaluation was restricted to nongrafted arteries and runoff vessels distal to bypass graft anastomoses, a total of 407 coronary segments with a diameter of >1.5 mm were available for analysis. In these 407 segments, invasive coronary angiography demonstrated a significant stenosis in 48 segments and absence of stenosis in 359 segments. By MDCT, 29 of 407 segments (7%) were un evaluable because of calcifications (n = 20) or motion artifacts (n = 9). In the remaining 378 coronary segments, sensitivity for the detection of significant stenoses (Figures 1 and 4) was 86% (38/44), with a specificity of 90% (302/334). Invasive coronary angiography demonstrated significant stenoses in 4 of 29 un evaluable segments. The results are summarized in Table 1.

**Per-Patient Analysis**

In all per-patient analyses, segments classified as un evaluable were regarded as positive (presence of stenoses) in MDCT. The accuracy for the detection of patients with at least 1 significant graft stenosis by MDCT was 96% (48/50) (sensitivity 100%, specificity 89%). For the detection of at least 1 stenosis in nongrafted arteries and the distal runoff vessels, sensitivity was 97% (35/36) with a specificity of 86% (12/14), which corresponds to an accuracy of 94% (47/50). In 17 patients, at least 1 coronary segment or bypass graft was classified as un evaluable, and in 18 patients, at least 1 stenosis was correctly detected by MDCT, yielding a sensitivity of 97% (35/36), specificity of 86% (12/14), and overall accuracy of 94% (47 of 50 patients). The results are summarized in Table 2.

**Discussion**

MDCT with retrospective ECG gating and intravenous injection of contrast agent has been shown to permit the assessment of bypass graft patency. With the use of 16-slice technology, sensitivities and specificities were between 95% and 100% for the assessment of graft patency. Sensitivities for the detection of significant stenoses (defined as a diameter reduction of >50%) were between 80% and 96% with specificities between 85% and 95%. Because of limited temporal and spatial resolution, distal graft anastomoses in particular frequently remained un evaluable. In addition, almost all studies were restricted to the evaluation of the bypass grafts. However, from a clinical point of view, the follow-up of patients with previous bypass surgery usually will also require assessment of the native coronary arteries, including nongrafted arteries and distal runoff vessels. Only 2 previous studies investigated both bypass grafts and native arteries using 4-slice and 16-slice technology. They found that between 27% and 40% of all distal runoff vessels with a diameter of ≥2.0 mm were un evaluable for stenosis because...
of motion artifacts and, especially, severe coronary calcifications.\textsuperscript{3,10}

Compared with previous scanner generations, 64-slice CT provides improved temporal and spatial resolution. Furthermore, with the simultaneous acquisition of 64 slices per rotation, the overall scan time and thus the breathhold time are significantly reduced. With regard to the evaluation of native coronary arteries, 64-slice technology demonstrated a higher diagnostic accuracy for the detection of significant stenoses compared with 16-slice scanners.\textsuperscript{13–17} Only 1 previous study used 64-slice MDCT in patients after bypass surgery,\textsuperscript{18} but analysis was limited to the grafts and did not include native arteries. In our study, we confirmed their conclusion that accuracy for detection of bypass occlusion and stenosis is high. Without exclusion of any bypass grafts (evaluability 100%), we found a very high diagnostic accuracy in the assessment of graft occlusions (accuracy 100%) and detection of graft stenoses (accuracy 95%). With regard to evaluation of the native coronary arteries, 9% of all coronary segments in native coronary arteries and 7% of segments in nongrafted and distal runoff vessels were unevaluable, mainly because of severe calcifications and, in a smaller number, motion artifacts. After the exclusion of unevaluable segments, diagnostic accuracy for the detection of significant stenoses (defined as a diameter reduction of \textgreater 50%) was 78% in all native coronary arteries and 90% for the nongrafted and distal runoff vessels. These values are lower than those that studies performed with 64-slice CT had found in patients without previous bypass surgery. In our own study, using the same technology and scan protocol, we achieved a diagnostic accuracy of 97% in 84 patients with suspected coronary artery disease. Only 4% of all coronary artery segments had to be excluded.\textsuperscript{17} The lower rates for evaluability and accuracy were mainly secondary to the prevalence of severe calcifications, which caused overestimation or, less frequently, underestimation of stenosis severity.\textsuperscript{24} Overestimation of stenosis degree is usually the result of the partial volume effect of CT (a consequence of its limited spatial resolution) or of the presence of coronary calcium.\textsuperscript{24} In these cases, overestimation of stenosis causes false-positive findings, thus decreasing specificity.

Limitations

Besides general limitations of cardiac CT (eg, radiation exposure, use of potentially nephrotoxic contrast agent, and a priori exclusion of patients with atrial fibrillation), the difficulties in the evaluation of severely calcified lesions remain a drawback in the CT evaluation of patients after bypass surgery. Metal clips placed alongside bypass grafts, especially internal mammary artery grafts, have frequently caused artifacts in previous studies.\textsuperscript{6,7,18} These artifacts are often aggravated by motion. In our study, no bypass graft or subsegment of a bypass graft was unevaluable because of the presence of a clip, which may be attributable to the high spatial and temporal resolution, as well as the strict protocol to lower heart rate, that we used. All the same, mainly because of calcifications in the native coronary arteries, only 66% of all patients (33/50) were completely evaluable in our study. Furthermore, the high prevalence of patients with at least 1 coronary or bypass graft stenosis—secondary to the fact that individuals with clinical evidence of disease progression constituted our patient population—resulted in high positive predictive values in the per-patient analyses (94% for bypass grafts, 90% for runoff vessels and nongrafted native coronary arteries, and 90% for the combination of bypass grafts, runoff segments, and nongrafted arteries). In a population with lower prevalence of disease, the positive predictive value may be lower, potentially leading to unnecessary invasive procedures if MDCT were used clinically. On the other hand, if MDCT is performed in populations with a high likelihood for progressive disease, the noninvasive procedure will help to avoid only a limited number of cardiac catheterizations (in our study only 12 of 50 patients), with substantial influence on the cost-effectiveness of this approach. A careful assessment of pretest likelihood of disease is therefore necessary before the clinical application of noninvasive imaging such as MDCT in certain patient populations after bypass surgery.

In conclusion, our results demonstrate the ability of 64-slice MDCT to assess the coronary status of patients after bypass surgery. Compared with previous scanner generations, 64-slice technology allows for more reliable evaluation of grafts and especially of the native coronary arteries in patients after bypass surgery. Although analysis can be challenging, the diagnostic accuracy of 94% on a per-patient basis implies that clinical applications may be possible in appropriately selected patient groups.

Disclosures

Drs Ropers, Kuettner, Anders, and Achenbach received speaker’s honoraria from Siemens Medical Solutions. Dr Achenbach has received research grants from Siemens Medical Solutions. The remaining authors report no conflicts.

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**CLINICAL PERSPECTIVE**

The increasing temporal and spatial resolution of multidetector computed tomography (CT) make imaging of the coronary arteries and bypass grafts (also referred to as coronary CT angiography) increasingly robust. Imaging of bypass grafts is relatively straightforward because these conduits have a larger diameter and are subjected to less motion than the coronary arteries. In assessing patients who present with chest pain after previous bypass surgery, however, it is clinically important to determine the status not only of the bypass grafts but also of the native coronary arteries distal to bypass grafts and of those vessels that did not receive bypass grafts at the time of surgery. As this study shows, this can be challenging because the native arteries tend to calcify heavily and often have a smaller caliber in patients after bypass surgery. Even though results have clearly improved over previous generations of multidetector CT scanners, reliable stenosis detection in the native coronary arteries remains challenging, so that the use of CT coronary (and bypass) angiography in patients after bypass surgery has to be considered carefully.
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*Circulation.* published online November 6, 2006;
*Circulation* is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 0009-7322. Online ISSN: 1524-4539

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