Computed Tomography Coronary Angiography

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Recent developments in computed tomography technology have made imaging of the coronary arteries possible. All the same, the rapid motion and small dimensions of the coronary vessels make coronary computed tomography angiography (coronary CTA) challenging. With the last generations of 16- and 64-slice computed tomography and adequate patient preparation (which includes lowering of the heart rate), rates of sensitivity ranging from 83% to 99% and specificity between 93% and 98% have been reported for the detection of coronary artery stenoses in comparison with invasive coronary angiography. The high negative predictive value (95% to 100%) found in these studies suggests that coronary CTA may be a useful diagnostic technique to rule out the presence of coronary stenoses in selected patients, especially those with a rather low pretest likelihood of disease. Imaging of coronary artery bypass grafts is reliable, but clinical applications can be hampered by difficulties in assessing the native coronary arteries in patients after undergoing bypass because of their often-severe calcification. The detection of in-stent restenosis is made difficult by artifacts caused by metal, especially in smaller stents. Finally, initial reports that coronary CTA allows the detection and, to a certain extent, also the characterization and quantification of noncalcified coronary atherosclerotic plaque are interesting, but they currently do not provide sufficient data to support clinical applications in the context of risk stratification. (J Am Coll Cardiol 2006;48:1919–28) © 2006 by the American College of Cardiology Foundation

Computed tomography (CT) techniques have in the past years been demonstrated to allow the visualization of coronary arteries and especially of the coronary lumen. The small dimensions of the coronary arteries, along with their rapid motion, make imaging very challenging, and the temporal and spatial resolution of CT had to be maximized to allow the use of coronary CT angiography (coronary CTA). Technical developments during the past several years—especially the introduction of 64-slice CT scanners—and growing experience concerning strategies for optimization of image quality have made coronary CTA quite reliable for some patient subgroups. However, coronary CTA is a new imaging modality and remains a technically challenging one. Various issues concerning scanner technology, image acquisition and reconstruction, image interpretation, and potential clinical applications need to be carefully considered and, in many fields, there are rapidly ongoing developments.

TECHNOLOGY OF CARDIAC CT

High temporal and spatial resolution are prerequisites for imaging of the coronary arteries. Conventional CT, because of the necessity of moving a heavy gantry with an X-ray tube and a detector system around the patient, traditionally has been a slow imaging modality. This encumbrance began to change when 4-slice spiral (or “helical”) CT systems were introduced around the year 2000. These systems provided a gantry rotation time of approximately 0.5 s, and with dedicated image reconstruction algorithms that required only data collected during one-half rotation to reconstruct one image (1), a temporal resolution of approximately 250 ms could be achieved. In addition, simultaneous registration of the patient’s electrocardiogram (ECG) permitted one to synchronize image reconstruction with the cardiac phase. In this way, contiguous cross-sectional images of the heart could be obtained, which all showed the heart in the same cardiac phase. Initial reports on visualization of the coronary artery lumen by 4-slice CT after intravenous injection of contrast agent were published in the year 2000 (2,3). All the same, because of the still relatively limited temporal and spatial resolution as well as the long duration of the required breath hold (as long as 40 s), the datasets frequently were of insufficient quality for interpretation (with approximately 30% of arteries classified as “unevaluable”) (4,5), which prevented clinical applications.

However, the initial success in visualizing the coronary arteries had triggered substantial interest in coronary CTA, and rapid improvements in CT technology ensued, aimed at permitting more reliable and accurate coronary artery imaging. The gantry rotation speed was increased to improve temporal resolution, slice collimation (thickness) was decreased to improve spatial resolution, X-ray tubes were strengthened to reduce image noise, and scanners allowed to acquire data in more and more slices simultaneously—from 4 to 8, 16, 32, 40, and 64 slices per
rotation (6–28). Increasing the number of slices allows one to cover a larger volume per rotation. It thus decreases the overall duration of data acquisition and, consequently, the duration of the breath hold and the necessary amount of contrast agent. Currently, 64-slice scanners with a gantry rotation times of 420 ms or shorter can be considered “state-of-the-art” equipment for the visualization of coronary arteries by CT.

However, it is important to note that the number of slices alone is not the one and only parameter that will influence image quality for coronary imaging. As mentioned previously, rotation speed, slice collimation, and tube output determine the temporal and spatial resolution and the mere number of slices only influences the overall duration of data acquisition. With current 64-slice scanners, the necessary breath hold is between 6 and 12 s and, thus, easy to perform. Simply adding a few more slices to existing scanner designs will therefore not lead to major improvements in the future.

Interestingly, recent publications show that industry is pursuing different concepts for the further development of cardiac CT. One approach is to increase the volume coverage (number of slices) so dramatically that imaging of the heart is possible in a single heart beat, which will make cardiac imaging less vulnerable to arrhythmias. Such systems will typically have 256 slices of approximately 0.5-mm collimation, and first results have been published (29,30). Spatial and temporal resolution remain unchanged. Another approach is to leave the number of slices at 64 but to combine 2 X-ray tubes and detectors in a single gantry, arranged at an angle of 90°. With this approach (dual-source CT), only a one-quarter rotation of the gantry is necessary to collect data from 180° of projections; temporal resolution is therefore twice as high as with a single X-ray tube and detector. It is expected that this will substantially reduce problems caused by motion artifact in clinical applications (31,32).

Data acquisition for coronary CTA. Most experienced centers prepare patients for a coronary CTA study by lowering the heart rate to <65 or even <60 beats/min—usually by administering oral or intravenous beta-blockers. Also, it is recommended to administer sublingual nitrates immediately before scanning to dilate the coronary arteries which, in my experience, substantially improves image quality.

Figure 1. Typical dataset as acquired by coronary computed tomography angiography (CTA) after intravenous injection of contrast agent (here: dual-source CT with a temporal resolution of 83 ms). (A) Transaxial image (0.75-mm reconstructed slice thickness) at the level of the proximal left anterior descending coronary artery. Cross sections of the proximal left anterior descending coronary artery (arrow) and left circumflex coronary artery (arrowhead) are visible. (B) Transaxial image at the level of the right coronary artery ostium. Smaller arrow: right coronary artery; larger arrow: left anterior descending coronary artery; arrowhead: left circumflex coronary artery. (C) Transaxial image at the midventricular level. Smaller arrow: right coronary artery; large arrow: left anterior descending coronary artery; arrowhead: left circumflex coronary artery. (D) Maximum intensity projections (here: 5-mm thickness in axial orientation) can be used to visualize longer segments of the coronary arteries and the relationship of main and side branches. Here, the left main and proximal left anterior descending (arrow) as well as left circumflex coronary artery (arrowhead) are displayed. (E) Another maximum intensity projection (8-mm thickness) in a double-oblique plane that parallels the right interventricular groove is used to display the entire course of the right coronary artery (arrows). (F) Curved multiplanar reconstruction (0.75-mm thickness) was used to visualize the right coronary artery (arrows). (G) Three-dimensional display of the heart and coronary arteries. Smaller arrow: right coronary artery; larger arrow: left anterior descending coronary artery; arrowhead: left circumflex coronary artery.
Although details of data acquisition will vary depending on scanner type, acquisition of a high-resolution "volume dataset" that covers the entire heart constitutes the core of the scan protocol. For this acquisition, between 50 to 120 ml of contrast agent are injected intravenously and the patient needs to perform a breath hold of 6 to 20 s (depending on the scanner generation and dimensions of the heart). The radiation exposure (effective dose) is estimated to be between 3 and 15 mSv, depending on the scan protocol (33–36). Electrocardiogram-correlated tube current modulation (reduction of tube current in systole) can reduce radiation exposure by 30% to 50% (36–38).

As mentioned previously, data acquired in projections of approximately 180° are necessary to reconstruct a cross-sectional image. These data can be obtained during one single 180° sweep of the CT gantry (and the temporal resolution would then correspond to one-half the rotation time). In this case, all the data used to reconstruct one image would stem from the same heart beat. An alternative is to piece together the 180° of data from several consecutive heart beats. The time window of data used out of each cardiac cycle for image reconstruction will then be shorter than one-half rotation of the gantry (ideally, for example, it would correspond to one-eighth rotation if data from four consecutive heart beats were used). However, the effectiveness of these so-called "multiphase" reconstruction algorithms depends on the relationship between heart rate, rotation time, and the speed with which the patient table is advanced into the scanner ("pitch"), and this relationship is not linear—the algorithms are more effective for some heart rates than for others. Also, it is important to note that the obtained images constitute an average of several heart beats, which may reduce sharpness.

The dataset obtained by coronary CTA will typically consist of approximately 250 to 350 transaxial cross-sectional images (Fig. 1). Slice thickness usually is chosen to be between 0.5 and 1.0 mm, and images will be spaced at a distance less than their thickness so that consecutive images have some overlap. The images are in most cases transferred to off-line workstations for further processing and evaluation. Two-dimensional forms of image reconstruction, such as "multiplanar reconstructions" or "maximum intensity projections," can facilitate data interpretation. Three-dimensional reconstructions are visually pleasing but rarely helpful to evaluate the data (Fig. 1). Importantly, image data can be reconstructed at any desired time instant in the cardiac cycle. Reconstruction of several data sets throughout the cardiac cycle thus permits for dynamic visualization of cardiac function (Fig. 2). Analysis of left ventricular wall motion can be obtained as a "byproduct" of coronary CTA and has been shown to provide accurate assessment of global and regional left ventricular function (39,40).

**Image quality and artifacts.** A regular heart rate is necessary for reliable imaging of the coronary arteries by computed tomography. Furthermore, the limited temporal and spatial resolution of CT can lead to artifacts that may make the images difficult or, in some situations, even impossible to evaluate. Motion can lead to blurring of the contours of the coronary vessels. The right coronary artery, which displays the most rapid motion during the cardiac cycle, is most frequently affected. Severe calcifications of the coronary arteries may obscure the coronary artery lumen because of partial volume effects. The high contrast also may aggravate the effect of motion artifacts, and calcification can therefore lead to false-negative and false-positive findings of coronary stenoses (Fig. 3). It has been shown in several studies that the accuracy for detection of coronary stenoses is lower in the presence of severe calcification (14,28,41,42). More importantly, it has been convincingly shown that heart rate is predictive of image quality and that a low heart rate substantially improves image quality, rate of evaluable arteries, and accuracy for stenosis detection (42–47).

**DETECTION OF CORONARY ARTERY STENOSES**

In experienced hands, a high sensitivity and specificity for the detection of hemodynamically relevant coronary artery stenoses can be achieved by recent generations of 16-slice and 64-slice CT (Fig. 4). Table 1 lists the results of recent
Coronary CTA has limitations and should not be expected to widely replace invasive, catheter-based diagnostic cardiac catheterization in the foreseeable future. Spatial resolution limits the ability of CTA to provide exact, quantitative measures of stenosis severity. In addition to limitations caused by calcium and rapid coronary motion, patients in atrial fibrillation or with other arrhythmias as well as patients with contraindications to iodinated contrast agent cannot be studied. As a purely anatomical imaging modality, the hemodynamic consequence of coronary artery stenoses cannot be assessed. Coronary CTA is furthermore a purely diagnostic tool. As opposed to invasive coronary angiography, there is no option for immediate intervention. Patients whose clinical presentation suggests a very high likelihood of having a stenosis (e.g., with absolutely typical chest pain and an unambiguously positive stress test) will thus most likely not benefit from so-called “noninvasive angiography” of any kind. However, the high negative predictive value may make the clinical application of coronary CTA useful in patients who are considered for invasive angiography because they are symptomatic but do not have a high pretest likelihood of coronary stenoses: if CTA clearly demonstrates normal coronary arteries, invasive angiography is not necessary. “Screening” applications of coronary CTA in asymptomatic individuals currently are not backed by clinical data. Although the use of coronary CTA for the detection of prognostically significant coronary lesions (e.g., main stem stenoses) in certain high-risk populations such as patients with diabetes are conceivable, the potential benefit remains to be proven in adequately designed, prospective studies.

**Bypass grafts.** The imaging of venous bypass grafts is less challenging than coronary arteries because they are larger and they move less rapidly than the coronary vessels (Fig. 5). Imaging of internal mammary artery grafts can in some cases be more difficult because of artifacts caused by metal clips placed alongside the bypass grafts. Several studies performed using 16-slice CT have shown that occlusions and stenoses of bypass grafts can be detected with very high accuracy (48–55) (Table 2). However, it has so far not been shown that CT imaging permits assessment not only of the bypass grafts but also of native coronary arteries distal to the

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**Figure 3.** Artifacts typically encountered in computed tomography coronary angiography. (A) An obvious motion artifact is present at the level of the mid-right coronary artery. A round cross section of the right coronary artery would be expected. Because of motion, the contour of the right coronary artery is blurred (larger arrows). In addition, on both sides of a small side branch, areas of very low computed tomography attenuation can be noted (smaller arrows). These artifacts also are caused by motion and typically are found adjacent to high-contrast structures (e.g., contrast-enhanced coronary arteries). (B) Severe coronary calcification in the proximal left anterior descending coronary artery (arrows). Calcifications of this extent can in some cases render the datasets unevaluable concerning the presence of coronary artery stenoses. (C) In some cases, the occurrence of a motion artifact is more subtle. The figure displays transaxial images at the level of the mid-right coronary artery, just distal to the ostium of a right ventricular side branch (arrowhead). On the left, the image was reconstructed at 70% of the cardiac cycle. A slight motion artifact is present (smaller arrow), which blurs the contour of a calcified plaque in the arterial wall (larger arrow) and also causes a low-density structure, which might be mistaken for noncalcified plaque components. On the right, the same image was reconstructed at 65% of the cardiac cycle. No motion artifact is present. The plaque is practically entirely calcified.
bypass grafts or arteries that have not received a bypass graft. The coronary arteries may, in fact, be challenging to assess by CT in patients after bypass surgery because they tend to calcify heavily and are frequently of small size (45,54). This limits the clinical usefulness of coronary CTA in patients who develop chest pain after bypass surgery because it

**Figure 4.** Shown is a patient with a high-grade stenosis of the left anterior descending coronary artery. (A) Transaxial computed tomography image (0.75-mm slice thickness) showing the stenosis, which involves the left anterior descending coronary artery and the relatively large diagonal branch. (B) In a 5-mm thick maximum intensity projection (transaxial orientation), the stenosis is more readily seen (arrow). Again, it can be seen that the stenosis involves the ostium of the left anterior descending coronary artery and a large diagonal branch in this bifurcation. (C) Curved multiplanar reconstruction of the left anterior descending coronary artery (larger arrow) shows the stenosis and the involvement of the side branch (smaller arrow). (D) Three-dimensional reconstruction (“volume rendering technique”). The stenosis of the left anterior descending coronary artery proximal to the bifurcation is clearly visible (arrow). However, the limited spatial resolution of the 3-dimensional reconstruction fails to demonstrate the presence of ostial stenoses of the 2 bifurcation branches. (E) Invasive coronary angiogram.

**Table 1.** Accuracy for Detection of Coronary Stenoses Using Coronary Computed Tomography Angiography With at Least 16 Slices (Comparison With Invasive Coronary Angiography)

<table>
<thead>
<tr>
<th>Author</th>
<th>n (Patients)</th>
<th>Collimation (mm)</th>
<th>Gantry Rotation (ms)</th>
<th>Sensitivity (%)</th>
<th>Specificity (%)</th>
<th>NPV (%)</th>
<th>n.e. (%)</th>
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<tbody>
<tr>
<td>Kuettner et al. (15)</td>
<td>124</td>
<td>16 × 0.75</td>
<td>375</td>
<td>85</td>
<td>98</td>
<td>96</td>
<td>7</td>
</tr>
<tr>
<td>Mollet et al. (16)</td>
<td>51</td>
<td>16 × 0.75</td>
<td>375</td>
<td>95</td>
<td>98</td>
<td>99</td>
<td>—</td>
</tr>
<tr>
<td>Martuscelli et al. (17)</td>
<td>64</td>
<td>16 × 0.625</td>
<td>500</td>
<td>89</td>
<td>98</td>
<td>98</td>
<td>—</td>
</tr>
<tr>
<td>Morgan-Hughes et al. (18)</td>
<td>58</td>
<td>16 × 0.625</td>
<td>500</td>
<td>83</td>
<td>97</td>
<td>97</td>
<td>2</td>
</tr>
<tr>
<td>Schuif et al. (19)</td>
<td>45</td>
<td>16 × 0.75</td>
<td>420</td>
<td>98</td>
<td>97</td>
<td>100</td>
<td>6</td>
</tr>
<tr>
<td>Hoffmann et al. (20)</td>
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<td>16 × 0.75</td>
<td>420</td>
<td>95</td>
<td>98</td>
<td>99</td>
<td>6</td>
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<td>Achenbach et al. (21)</td>
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<td>375</td>
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<td>96</td>
<td>99</td>
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<td>Leschka et al. (22)</td>
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<td>94</td>
<td>97</td>
<td>99</td>
<td>—</td>
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<tr>
<td>Raff et al. (23)</td>
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<td>64 × 0.6</td>
<td>330</td>
<td>86</td>
<td>95</td>
<td>98</td>
<td>12</td>
</tr>
<tr>
<td>Leber et al. (24)</td>
<td>59</td>
<td>64 × 0.6</td>
<td>330</td>
<td>73</td>
<td>97</td>
<td>99</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>88*</td>
<td>97*</td>
<td>99*</td>
<td>—</td>
</tr>
<tr>
<td>Mollet et al. (25)</td>
<td>52</td>
<td>64 × 0.6</td>
<td>330</td>
<td>99</td>
<td>95</td>
<td>99</td>
<td>2</td>
</tr>
<tr>
<td>Ropers et al. (26)</td>
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<td>64 × 0.6</td>
<td>330</td>
<td>95</td>
<td>93</td>
<td>99</td>
<td>4</td>
</tr>
<tr>
<td>Fine et al. (27)</td>
<td>66</td>
<td>64 × 0.6</td>
<td>330</td>
<td>95</td>
<td>96</td>
<td>95</td>
<td>6</td>
</tr>
</tbody>
</table>

Studies performed by 16-slice scanners that did not use all 16 detector rows for data acquisition are not listed. *Analysis in proximal and mid-coronary segments. n.e. = not evaluable; NPV = negative predictive value.
Figure 5. Computed tomography angiography in a patient with 3 venous coronary artery bypass grafts. (A) Transaxial cross section showing the aortic anastomosis and a cross section of the mid-segments of the venous graft to the left anterior descending coronary artery (arrows). In addition, a cross section of the left circumflex graft is seen (arrowhead). (B) Transaxial 5-mm thick maximum intensity projection showing the aortic anastomosis of the right coronary artery bypass graft (double arrows). In addition, a cross section of the left anterior descending graft (larger arrow) and of the left circumflex graft (arrowhead) are visible. The proximal left coronary artery is seen, with a high-grade stenosis of the left main coronary artery proximal to the bifurcation (smaller arrow). The coronary arteries are of narrow lumen and have substantial calcification. (C) Curved multiplanar reconstruction of the venous graft to the right coronary artery (arrows). The double arrows indicate the anastomosis to the distal right coronary artery. (D) Three-dimensional reconstruction showing bypass graft to left anterior descending (larger arrow), to left circumflex (arrowhead), and to right coronary artery (smaller arrow).

Table 2. Results of 16-Slice Computed Tomography Coronary Angiography for the Assessment of Bypass Grafts in Comparison With Invasive Coronary Angiography

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Sensitivity (%)</th>
<th>Specificity (%)</th>
<th>n.e. (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nieman et al. (48)</td>
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<td></td>
<td></td>
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<tr>
<td>Bypass occlusion</td>
<td>100</td>
<td>98</td>
<td>0–5</td>
</tr>
<tr>
<td>Bypass stenosis</td>
<td>60–83</td>
<td>88–90</td>
<td>5–10</td>
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<tr>
<td>Native coronary stenosis</td>
<td>79–89</td>
<td>72–75</td>
<td>31–34</td>
</tr>
<tr>
<td>Martuscelli et al. (49)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bypass occlusion</td>
<td>100</td>
<td>100</td>
<td>9–12</td>
</tr>
<tr>
<td>Bypass stenosis</td>
<td>90</td>
<td>100</td>
<td>9–12</td>
</tr>
<tr>
<td>Schlosser et al. (50)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bypass occlusion</td>
<td>100</td>
<td>100</td>
<td>12</td>
</tr>
<tr>
<td>Bypass stenosis</td>
<td>90</td>
<td>100</td>
<td>12</td>
</tr>
<tr>
<td>Chiurlia et al. (51)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Bypass occlusion</td>
<td>100</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Bypass stenosis</td>
<td>96</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Moore et al. (52)</td>
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<tr>
<td>Bypass occlusion</td>
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<td>100</td>
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<td>Bypass stenosis</td>
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<td>99</td>
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<tr>
<td>Burgstahler et al. (53)</td>
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<tr>
<td>Bypass occlusion</td>
<td>100</td>
<td>100</td>
<td>5</td>
</tr>
<tr>
<td>Bypass stenosis</td>
<td>100</td>
<td>93</td>
<td>0</td>
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<tr>
<td>Salm et al. (54)</td>
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<td>Bypass occlusion</td>
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<td>100</td>
<td>8</td>
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<td>Bypass stenosis</td>
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<td>94</td>
<td>8</td>
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<tr>
<td>Stenosis in nongrafted vessels</td>
<td>100</td>
<td>89</td>
<td>24</td>
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<td>Anders et al. (55)</td>
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<td>90–82</td>
<td>16–22</td>
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</table>

In 2 of the studies, analysis of native coronary arteries was included. Although the accuracy for the detection of stenoses and occlusions in bypass grafts is uniformly high, reliable assessment of native coronary arteries was not possible.

n.e. = not evaluable.
usually will be necessary to assess the status both of the bypass grafts and of the native coronary arteries. Most likely, 64-slice CT will permit more complete and reliable assessment of patients, but this remains to be proven.

**Coronary artery stents.** Because of artifacts caused by metal, the visualization of the lumen within coronary artery stents by multidetector CT is more challenging than the assessment of the native coronary arteries (Fig. 6). Only a small number of studies have evaluated the value of MDCT to detect in-stent restenosis (56–61). In those studies, most performed by 16-slice CT, the rate of evaluable stents was low and, even in assessable stents, sensitivity for the detection of in-stent restenosis was only between 54% and 83%.

Next to the type of scanner used, several factors that influence the accessibility of stents have been identified. They include the type of stent, as shown in phantom studies (61,62). Also, the available data suggest that stent diameter plays a significant role. In the study by Schuijf et al. (57), 28% of stents with a diameter ≤3.0 mm, but only 10% of stents with a diameter >3.0 mm were un evaluable. In a study by Gilard et al. (61), which included only stents implanted in the left main coronary artery—with a large mean diameter of 3.9 mm—all stents were assessable, and all 4 restenoses were detectable by CT. In another study by the same group, with 232 included stents—the largest such study to date—49% of stents with a diameter ≤3.0 mm and 19% of stents with a diameter >3.0 mm could not be evaluated (56). Gaspar et al. (60) found that with 40-slice CT, all of 111 stents were evaluable (with a mean stent diameter of 3.3 mm), but only 72% of in-stent restenoses were detected. The use of 64-slice scanners may improve coronary stent visualization by CT (62,63), but the ability of coronary CTA to replace invasive angiography in unselected patients with previous coronary stenting has not been demonstrated.

**Imaging of coronary atherosclerotic plaque.** Several publications have shown that, in addition to the detection of coronary artery stenoses, multidetector CT also permits the visualization of nonstenotic plaque, both calcified and noncalcified (Fig. 7). Sensitivities for the detection of plaque—whether calcified or noncalcified—have been reported to be approximately 80% to 90% (64–68).

Again, patients were somewhat preselected in these studies. Also, most studies did not evaluate the accuracy for detection of single plaques, but of coronary segments that contain plaque and, in many cases, the detection of plaque was, in fact, driven by the detection of calcified plaque, with substantially lower sensitivity to detect purely noncalcified plaque (65,68). One study has demonstrated that coronary CTA can analyze the extent of remodeling in coronary atherosclerotic lesions (69). According to current knowledge, the ability of CT to quantify the size and volume of plaque is limited (65,68,70). Correlation coefficients for plaque area and volume ranged from $r = 0.55$ to $r = 0.80$ (65,68,70). On a per-segment basis, CTA underestimated the plaque volume when compared with intravascular ultrasound in a study performed by 16-slice CT (mean plaque volume per segment of $24 \pm 35 \text{ mm}^3$ in CT vs. $43 \pm 60 \text{ mm}^3$ for intravascular ultrasound, $p < 0.001$) (65). A more detailed analysis performed using 64-slice CT showed that there was a tendency to overestimate the volume of calcified plaque ($65.8 \pm 110.0 \text{ mm}^3$ vs. $53.2 \pm 90.3 \text{ mm}^3$, $p = 0.19$), whereas the volume of noncalcified and “mixed” plaque was systematically underestimated in CT ($59.8 \pm 76.6 \text{ mm}^3$ vs. $67.7 \pm 67.9 \text{ mm}^3$ and $47.7 \pm 87.5 \text{ mm}^3$ vs. $57.5 \pm 99.4 \text{ mm}^3$, $p < 0.03$) (68).

Similarly, initial observations have shown that, on average, the CT attenuation within “fibrous” plaques (mean attenuation values of 91 to 116 Hounsfield units) is greater than within “lipid-rich” plaques (mean attenuation values of 47 to 71 Hounsfield units) (66,68,70–75). However, the large variability of measured density values within plaques (74) and the substantial influence of contrast density within the coronary lumen on density

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**Figure 6.** Imaging of coronary artery stents. (A) A stent with a diameter of 3.5 mm in a distal left main coronary artery, immediately proximal to the bifurcation, is assessable by coronary computed tomography angiography and shows absence of in-stent restenosis (arrow). (B) A stent with a diameter of 3.5 mm in a right coronary artery shows artifacts within the stent lumen and cannot be assessed by computed tomography.
values measured within plaques (76,77) currently do not allow the use of CT for the classification of a single coronary atherosclerotic plaque.

**SUMMARY AND OUTLOOK**

Computed tomography has gone through rapid development during the past years, much of which was driven by the desire to provide reliable and accurate coronary angiography by CT. In fact, visualization of the coronary arteries has become increasingly stable and, with recent scanner generations, adequate patient selection, and experience in acquisition and interpretation of data, significant coronary artery stenoses can be reliably ruled out by multi-detector CT in some patient subgroups. Currently, the use of coronary CTA does not constitute a broad replacement for diagnostic coronary angiography, but available data indicate that, in certain clinical situations, it may be an alternative for selected patients. The main area of interest is currently the use of CT to rule out stenoses in patients with possible coronary artery disease but a rather low pretest likelihood of significant disease. This pertains to "stable" patients but also potentially to patients who present with acute chest pain, in whom coronary artery disease may often not be very likely. The accurate definition of the potential role of coronary CTA to rule out disease in a clinical context, including analysis of cost-effectiveness aspects and of the possibility of developing organizational structures that will provide for "24/7" availability of competent data acquisition and interpretation, will be necessary next steps that must be pursued with high priority. Finally, more widespread availability of 16- and 64-slice scanners as well as subsequent scanner generations will lead to an increase in sites that offer CT imaging of the heart, which creates issues of education, training, and quality control.

**REFERENCES**

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