Coronary angiography with multi-slice computed tomography

Koen Nieman, Matthijs Oudkerk, Benno J Rensing, Peter van Ooijen, Arle Munne, Robert-Jan van Geuns, Pim J de Feyter

Summary

Background A new generation of subsecond multi-slice computed tomography (MSCT) scanners, which allow complete coronary coverage, are becoming widely available. We investigated the potential value of MSCT angiography in a range of coronary disorders.

Methods We studied 35 patients, including 11 who had undergone percutaneous transluminal coronary angioplasty and four who had had coronary-artery bypass grafts, by both MSCT and conventional coronary angiography. After intravenous injection of a non-ionic contrast medium with high iodine content, the entire heart was scanned within a single breath-hold. The total examination time was no more than 20 min. The retrospective electrocardiographically gated reconstruction source images and three-dimensional reconstructed volumes were analysed by two investigators, unaware of the results of conventional angiography.

Findings In the 31 patients without previous coronary surgery, 173 (73%) of the 237 proximal and middle coronary segments were assessable. In the assessable segments, 17 of 21 significant stenoses (>50% reduction of vessel diameter) were correctly diagnosed. The non-assessable segments included four lesions. Misinterpretations were mainly the result of severe calcification of the vessel wall. Segments with implanted stents were poorly visualised, but stent patency could be assessed in all cases. Of the 17 segments of bypass grafts, 15 were assessable and four of five graft lesions were detected. Two cases of anomalous coronary anatomy could be visualised well.

Interpretation These preliminary data suggest that MSCT allows non-invasive imaging of coronary-artery stenoses and has potential to develop into a reliable clinical technique.

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Introduction

Conventional X-ray coronary angiography is the standard of reference for the assessment of coronary-artery disease. It is an invasive and potentially harmful procedure with a small risk of serious events (arrhythmia, stroke, coronary-artery dissection, death). Furthermore, the catheterisation procedure involves admission to hospital and discomfort for the patient. Therefore, conventional angiography should be undertaken only on strict clinical indications.

Magnetic resonance imaging and electron-beam computed tomography have been investigated for non-invasive coronary imaging. However, both have significant limitations in reliable visualisation of the coronary arteries.3,4 Multi-slice computed tomography (MSCT) scanners have lately become widely available. These scanners have the potential to allow non-invasive coronary angiography within a single breath-hold by use of a rotation speed of 0·5 s and sophisticated algorithms for retrospective electrocardiographic (ECG) gating. We aimed in this study to assess the diagnostic potential of non-invasive MSCT angiography for the assessment of coronary-artery disease.

Methods

35 patients (27 male, eight female; mean age 59 years [SD 11; range 28–77]) underwent both conventional and MSCT angiography of the coronary arteries or bypass grafts. 11 patients had previously undergone percutaneous transluminal coronary angioplasty with stent implantation, and four coronary-artery bypass grafting. Two patients had a congenital coronary-artery variant. Patients were included only if they had a regular heart rhythm and good pulmonary function. Exclusion criteria were: previous allergic reactions to iodine-containing contrast media, severe renal failure, pregnancy, an unstable clinical condition, or circumstances of any kind that would not allow the patient to lie in a supine position. All patients scheduled for conventional coronary angiography at our centre were approached until the scanning slots allocated to the research project were filled. The study protocol was approved by the hospital's ethics committee and all patients gave informed consent.

A new generation of multi-detector-array CT scanners operate at an increased rotation rate (2 per s) and produce up to four slices simultaneously.5 These developments permit high-speed scanning of large volumes with a high in-plane resolution, as well as an improved Z-axis resolution and a substantial improvement in the inter-slice correlation.6 Partial scan-reconstruction techniques, which apply a 90–180° reconstruction algorithm, improve the temporal resolution to 250 ms. These algorithms also reduce the effective slice thickness at an acceptable increase in noise and reduction in contrast.7 Recent modifications in the reconstruction software have further reduced the virtual temporal resolution at higher heart rates by combining the data from several heart cycles in one image, shortening the effective acquisition intervals to 125 ms. The in-plane spatial resolution of the MSCT scanner is nine line pairs per cm.8 We used retrospective gating, which allows post-scan acquisition window selection and optimum gating.9 This approach improves the image quality and decreases the sensitivity to arrhythmia and ECG noise.

The patient was placed within the gantry of an MSCT scanner (Somatom plus 4 Volume Zoom, Siemens AG, Erlangen, Germany) in a supine position. Leads were attached for simultaneous ECG and image recording necessary for inter-related image reconstruction. According to the expected location of the coronary arteries, obtained from the coronal scout view, the scan volume was defined, depending on the patient’s ability to cooperate and characteristics (breath-hold, heart rate) and
the scan variables (pitch, slice thickness, scan time). For arterial grafts, the area to be covered was extended to the origin of the left internal mammary artery. Fixed scanning variables included the 0.5 s rotation time and a tube voltage of 140 kV. We used a protocol of four slices with a collimated slice thickness of 1 mm. The pitch (table feed per rotation divided by the single collimated slice thickness) was set at 1.5 for heart rates below 80 beats per min and 2.0 for faster heart rates. Depending on the selected pitch and volume to be covered, the total scan time was between 30 s and 40 s. After thorough instruction, most of the patients were able to suspend respiration for 40 s. To facilitate adequate breath-holding, the patients were asked to hyperventilate before the start of the scan. Optimum contrast between blood and surrounding tissue was achieved by injection of 150 mL contrast agent with a high iodine content (350 g iodine per L; Iomeprol, Bracco-Byk Gulden, Konstanz, Germany) into the antecubital vein at a rate of 3.5–4.0 mL/s. Scanning was started after 20 s. The radiation dose was estimated to be 4.9 mSv (ICRP 60, Monte Carlo, Aarhus University Hospital).

The acquired CT and ECG data were sent to a separate workstation, and dedicated cardiac work-in-progress reconstruction software (Siemens Cardio Package, Siemens AG; and MatLab version 5.3, MathWorks Inc, Natick, MA, USA) was used to reconstruct the images. Transverse tomograms were reconstructed from the acquired CT data during a preselected interval of 125–250 ms, depending on the heart rate, within the cardiac cycle. To minimise motion artefacts, the reconstruction window was positioned in the mid to late diastolic phase at a fixed point before the next R wave. If ECG irregularities occur, the retrospective ECG gating can be corrected manually. Owing to the spiral motion of the detector row, the 4\(\times\)11003 mm, a stack of 130–150 slices is created. Further parameters include a 150 mm field of view and a 512\(\times\)512 matrix, which results in an interpolated voxel size of 0.3\(\times\)0.3\(\times\)0.8 mm\(^3\).

The images were further processed on separate graphic workstations (Indigo 2 and O2, SGI, Mountain View, CA) by means of special software packages (Vitrea and Voxel View, Vital Images, Plymouth, MN, USA). To analyse the coronary arteries, several volume-rendering techniques were used. Multiplanar reformatting allows the investigator to place and manoeuvre cross-sectional image planes through a three-dimensional volume. High-level (>150 Hounsfield units) and narrow window settings were used to discriminate between contrast-enhanced lumen and the vessel wall. Three-dimensional volume-rendering techniques with manual segmentation of overlying structures (Voxel View, Vital Images) were used to demonstrate the three-dimensional course of the cardiac vessels around the heart. All scans were evaluated by consensus of two experienced investigators, who were unaware of the conventional angiographic results. If consensus could not be reached, a third investigator was consulted.

Cardiac catheterisation and contrast-enhanced X-ray coronary angiography were done according to standard techniques. Multiple views of the coronary arteries were obtained and stored on a CD-ROM. The angiograms were evaluated by two cardiologists without knowledge of the MSCT angiographic findings. In cases of disagreement, a third cardiologist was consulted. Coronary-artery segments were classified as significantly stenosed (diameter reduction >50%) or as normal or not significantly stenosed (diameter reduction ≤50%).

We investigated the proximal and middle segments of the coronary-artery tree, which includes the proximal, middle, and distal segments of the right coronary artery, the left main artery, the proximal and middle segments of the left anterior descending artery, and the proximal and middle segments of the left circumflex artery, according to the guidelines of the American Heart Association.\(^{10}\) Thus, eight segments per patient were available for assessment. After localisation, the respective segments were first semiquantitatively classified as assessable or not. Segments with stents were excluded. Results from the two angiographic techniques were compared, with conventional angiography serving as the standard of reference.

![Figure 1: Left anterior oblique projection with cranial angulation by MSCT coronary angiography (A) and conventional coronary angiography (B)](image-url)

Occlusion (black arrow) of the left anterior descending artery (LAD) with collateral filling of the distal LAD as well as a severe stenosis (white arrow) of the second diagonal branch (D2), were detected with both modalities. The septal branch (S1) and the first diagonal artery (D1) are well visualised. The proximal left circumflex artery (LCX) appears severely calcified on the MSCT angiogram. LM=left main coronary artery.
Results
The median time between conventional and MSCT angiography was 9 days (range 0–39). During the MSCT investigations, no severe complications occurred. Two patients developed an allergic skin reaction, one within 1 h and the other 48 h after injection of the contrast agent.

Average investigation time, including preparation and scanning, was less than 20 min. Reconstruction of the images took about 45 min, preparation of the three-dimensional volumes up to 1 h, and each evaluation around 15 min.

Among the 31 patients without previous coronary surgery, the conventional coronary angiogram showed disease of one vessel in eight patients, two vessels in four, three vessels in three, and four vessels in one (including the left main artery). 15 patients showed no significant lesions. 248 artery segments were available for analysis. After exclusion of 11 stented segments, 73% (173 of 237 segments) were assessable by MSCT (table 1). The reasons why segments could not be assessed are given in table 2. The non-assessable segments included three lesion-containing segments of right coronary artery and one of the left main artery.

17 (81%) of 21 significant lesions were correctly detected, and 148 (97%) of 152 normal or non-significantly diseased segments were correctly diagnosed by MSCT (figure 1, table 3). Arterial calcification (figure 2), as well as blending with overlying vessels, led to the four false-positive and four false-negative interpretations (table 3).

Of the 11 patients with intracoronary stents, six were scanned within 2 weeks of the procedure and five were scanned when they presented with recurrent symptoms. All stents could be localised and related to the vessel in which they were positioned. Beam hardening and partial volume artefacts hampered visualisation of the lumen within the stent. Nevertheless, the vessel segment distal to the stent could be recognised in all cases, indicating stent patency, confirmed by conventional angiography.

Four patients (three men, one woman) had previously undergone coronary-artery bypass grafting. The average time between surgery and the MSCT scan was 9 years (range 4–13). All patients underwent conventional coronary angiography because of recurrent symptoms. The group consisted of three arterial (five anastomoses) and three venous grafts (with 12 distal anastomoses). The investigators were familiar with the surgeon’s operative report but unaware of the results of conventional angiography. Image quality was adequate for assessment in 15 of 17 available conduits. Two arterial conduits could not be assessed owing to the small vessel size and artefacts caused by metal clips. No stenoses were observed by either MSCT or conventional angiography in the arterial conduits. In the venous grafts, two stenoses and two completely occluded conduits were correctly diagnosed by MSCT (figure 3). One vessel apparently occluded on MSCT was patent on conventional angiography.

Table 1: Number of assessable segments in 31 patients

<table>
<thead>
<tr>
<th>Segment</th>
<th>Number assessable/total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right coronary artery</td>
<td></td>
</tr>
<tr>
<td>Proximal</td>
<td>26/29 (90%)</td>
</tr>
<tr>
<td>Middle</td>
<td>18/30 (60%)</td>
</tr>
<tr>
<td>Distal</td>
<td>20/31 (65%)</td>
</tr>
<tr>
<td>Left main artery</td>
<td>29/30 (97%)</td>
</tr>
<tr>
<td>Left anterior descending artery</td>
<td></td>
</tr>
<tr>
<td>Proximal</td>
<td>28/30 (93%)</td>
</tr>
<tr>
<td>Middle</td>
<td>20/26 (77%)</td>
</tr>
<tr>
<td>Left circumflex artery</td>
<td></td>
</tr>
<tr>
<td>Proximal</td>
<td>21/30 (70%)</td>
</tr>
<tr>
<td>Middle</td>
<td>11/31 (38%)</td>
</tr>
<tr>
<td>Total</td>
<td>173/237 (73%)</td>
</tr>
</tbody>
</table>

11 segments with an implanted stent were excluded.

Table 2: Reasons for non-assessability of vessel segments

<table>
<thead>
<tr>
<th>Reason</th>
<th>Number assessable/total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cardiac motion/arrhythmia</td>
<td>0 0 2 14 16</td>
</tr>
<tr>
<td>Extensive calcifications</td>
<td>1 6 5 3 15</td>
</tr>
<tr>
<td>Small vessel (&lt;1.5 mm)</td>
<td>0 0 12 0 12</td>
</tr>
<tr>
<td>Adjacent contrast-filled structures*</td>
<td>0 1 6 3 10</td>
</tr>
<tr>
<td>Non-cardiac motion (breathing)</td>
<td>0 0 2 5 7</td>
</tr>
<tr>
<td>Poor opacification</td>
<td>0 1 2 1 4</td>
</tr>
</tbody>
</table>

*Veins or ventricle.

Table 3: Diagnostic accuracy of MSCT coronary angiography to detect stenoses of >50% diameter

<table>
<thead>
<tr>
<th></th>
<th>Left main</th>
<th>Left anterior descending</th>
<th>Left circumflex</th>
<th>Right coronary</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>True positive</td>
<td>0</td>
<td>6</td>
<td>2</td>
<td>9</td>
<td>17</td>
</tr>
<tr>
<td>True negative</td>
<td>29</td>
<td>38</td>
<td>28</td>
<td>53</td>
<td>148</td>
</tr>
<tr>
<td>False positive</td>
<td>0</td>
<td>2 (C, V)</td>
<td>0</td>
<td>2 (C, U)</td>
<td>4</td>
</tr>
<tr>
<td>False negative</td>
<td>0</td>
<td>2 (C, C)</td>
<td>2 (C, V)</td>
<td>0</td>
<td>4</td>
</tr>
</tbody>
</table>

Misinterpretations caused by calcifications (C), overlying vessel (V); unknown cause (U).
Two patients presented with anomalous anatomy of the coronary vessels. In both cases the coronary anatomy could be presented in a readily interpretable three-dimensional image (figure 4).

Video recordings of four angiograms are available with this paper on The Lancet’s website (www.thelancet.com).

Discussion

We found that significant stenoses (>50% reduction in diameter) in the proximal and middle coronary arteries could be detected by MSCT coronary angiography. Segments of the left main and left anterior descending arteries were visualised in most cases (90%), and six of eight stenoses were correctly detected. Visualisation of the right coronary artery is more sensitive to motion artefacts, which resulted in a lower proportion of interpretable segments (71%). Nevertheless, all seven lesions were correctly diagnosed. The left circumflex artery was the most difficult to examine. This artery is small in many people, and it easily blends with adjacent contrast-filled structures such as the great cardiac vein and the left atrium. Only 51% of the circumflex segments were assessable, and two of four stenoses were detected.

In the presence of intracoronary stents, high-density artefacts, combined with partial volume effects, prevent adequate assessment of the small vessel lumen within the struts of the stent. However, patency can be assessed if enhancement by contrast medium is observed in the vessel segment distal to the stent. In larger-diameter vessels, such as the carotid arteries, the in-stent lumen can be assessed quite well. Assessability of the stented segments is expected to increase with the improvement of spatial resolution and the use of less radio-opaque alloys for stents. Coronary-artery bypass grafts, because of their size and relative immobility, can be reliably imaged. In patients with an anomalous origin or course of the coronary arteries, MSCT displays, in contrast to conventional angiography, a three-dimensional map of the coronary anatomy, which allows easy identification of a high-risk course of a coronary artery between the pulmonary artery and the aorta (figure 4). Despite these satisfying initial results, some technical limitations remain. Although manual repositioning of the R-wave indicators during retrograde gating improves the synchronisation of acquisition intervals between consecutive heartbeats, cardiac motion artefacts cannot be entirely prevented. For instance, the middle segment of the right coronary artery, which is mobile during the cardiac cycle, runs perpendicular to the transverse slices. Consequently, this vessel is more vulnerable to arrhythmia and inaccurate triggering, which results in discontinuity between the consecutive slices. Movement of the patient, such as breathing, also causes motion artefacts, which can be reduced by thorough instruction before scanning.

The presence of extensive calcifications can complicate correct assessment of the lumen of the coronary arteries. The high-contrast calcium depositions cannot be sufficiently isolated from the contrast-enhanced vessel lumen and may result in non-assessable segments or misinterpretation. Nevertheless, severe calcification of the coronary arteries is related to coronary-artery disease, and its detection will contribute to clinical decision-making.

Figure 3: Conventional coronary angiography (A, B, C) and MSCT angiography (D, E) of a patient with previous coronary-artery bypass grafting

Left internal mammary artery (LIMA) is anastomosed to the left anterior descending artery (LAD). A saphenous vein graft (SVG) jumps via the marginal branch (RM) to the posterolateral branch (RPL) and the right descending posterior branch (RDP). The last segment shows a significant lesion (arrow head). SC=coronary sinus; GCV=great cardiac vein.
spatial orientation of vessels and are able to identify and quantify calcium deposition within the vessel wall.

**Contributors**

Koen Nieman contributed to the study concept and design, literature research, clinical studies, and data acquisition and analysis, and was responsible by preparation of the report. Mathijus Oudkerk contributed to concept, design, analysis, and editing and review of the report. Benno Rensing contributed to concept, design, literature research, analysis, and editing and review of the report. Peter van Ooijen contributed to data acquisition and review of the report. Arie Munne contributed to design, clinical studies, data acquisition, and review of the report. Robert van Geus contributed to concept, design, clinical studies, and review of the report. Pim de Feyter contributed to concept design, literature research, data analysis, and editing and review of the report.

**References**