Rapid and complete coronary arterial tree visualization with magnetic resonance imaging: feasibility and diagnostic performance

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Aims Current imaging of the coronary arteries with magnetic resonance coronary angiography (MRCA) is restricted to limited coverage of the coronary arterial tree and requires complex planning. We present and evaluate a rapid, single-scan MRCA approach with complete coverage of the coronary arterial tree.

Methods and results Fifty-five consecutive patients with suspected coronary artery disease underwent free-breathing, navigator-gated MRCA using a single three-dimensional volume with transversal slice orientation and nearly isotropic spatial resolution (1.2 × 1.2 × 1.4 mm³) with coverage of the whole heart [steady-state free precession (SSFP); TR/TE/flip angle: 5.3 ms/2.6 ms/90°; Philips Intera CV 1.5T]. The acquisition duration per heart beat was individually adapted to the cardiac rest period. Correction of respiratory motion was done using a patient-specific affine prospective navigator technique (two navigator beams: cranio-caudal position on the dome of the right hemidiaphragm and anterior–posterior position on the right chest wall; gating window 10 mm). The diagnostic performance of MRCA in detecting significant coronary stenoses was evaluated against X-ray angiography as the standard of reference (32 patients) using a 16-segment model. Effective scan duration was 18 ± 6 min (navigator efficiency: 68 ± 14%). In all examinations, the main epicardial vessels [left anterior descending artery (LAD), left circumflex artery (LCX), and right coronary artery (RCA)], including their distal segments and major side branches (number of visible side branches: LAD, 2.0 ± 0.9; LCX, 1.5 ± 0.6; RCA, 2.3 ± 0.9), were reliably visualized. Eighty-three per cent of all coronary segments were evaluable; sensitivity, specificity, and diagnostic accuracy were 78, 91, and 89%, respectively.

Conclusion The combination of an imaging sequence with an intrinsically high contrast (SSFP) and a sophisticated navigator technique (affine transformation) resulted in high quality, high resolution imaging of the whole coronary arterial tree within a short examination duration. Robustness and diagnostic accuracy may allow for a routine application in the near future.

Introduction

In the last decade, magnetic resonance coronary angiography (MRCA) emerged as a non-invasive tool for diagnosing coronary artery disease.1,2 Although MRCA has been evolving rapidly,3–5 current approaches are limited by partial coverage of the coronary arterial tree. This causes an additional drawback because extensive scout scanning and sophisticated planning need to be performed prior to the actual image acquisition. The acquisition of a large three-dimensional volume with transversal coverage of the entire heart would reduce the time for planning and thus shorten and simplify the examination. Weber et al.6 were the first to describe and successfully employ three-dimensional whole-heart scanning in volunteers. These authors found whole-heart scanning to be advantageous when compared with single volume imaging.

Besides the shortening of the total examination duration, further improvement of MRCA might be achieved by using optimized MR sequences in conjunction with improved respiratory and cardiac motion compensation techniques. Recently, the use of steady-state free precession (SSFP) sequences proved to be advantageous: first reports on SSFP sequences for coronary MRA yielded an improved vessel border definition7,8 because of the high signal to noise ratio and the intrinsically high contrast.9,10 Regarding effective compensation for respiratory motion, it was found that free-breathing, navigator-gated MRCA is superior to breath-hold imaging in the majority of patients.11 Further improvements of the navigator technique are expected from the

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application of multiple navigators which not only correct for cranio-caudal movement but also for translational, rotational, scale, and shear motions.12

To ensure complete freezing of cardiac motion, data acquisition is generally limited to the coronary artery rest period (mainly found during mid-diastole). Recently, it was reported that the cross-correlation between images of consecutive heart-phases represents an exact measure for cardiac motion13 and allows for the automated and user-independent detection of the cardiac acquisition window.14

The objective of the present study was to design an advanced approach for MRCA which combines three-dimensional imaging of the entire heart with the recently optimized techniques for respiratory and cardiac motion compensation using an SSFP sequence. Feasibility and diagnostic performance of this new approach were evaluated.

Methods

Subjects

The prospective study was approved by the Ethics Committee of the Virchow Klinikum and Charité, Berlin, Germany. Fifty-five consecutive patients (38 men, 17 women; mean age: 58 ± 11 years; range: 28–74 years) with clinically suspected coronary artery disease or prior PTCA (no prior stent implantation or coronary artery bypass graft operation) were studied. Written informed consent was obtained from all patients. First, in a pilot study of 20 patients with prior negative stress testing, the feasibility of the proposed new MRCA approach was evaluated. Secondly, after completing the feasibility study, the diagnostic performance of MRCA was assessed in 35 additional patients scheduled for invasive coronary angiography because of clinically suspected coronary artery disease. Patients with contraindications to MR imaging (non-compatible biometalic implants or claustrophobia) or atrial fibrillation were not considered for study inclusion.

MR imaging

All patients were examined in the supine position using a whole-body MR system (Philips Intera CV 1.5T, Best, The Netherlands) equipped with a PowerTrak6000 gradient system (23 mT/m; 219 μs rise time) and specifically designed software (Release 9, BACCHUS-Patch). A five-element cardiac synergy coil was used for signal detection. Cardiac synchronization was performed using four electrodes placed on the left anterior hemithorax (vector-electrocardiogram) and scans were triggered on the R-wave of the ECG.15 A rapid gradient echo sequence (multistack, multislice survey, SSFP, TR/TE/flip angle: 4.0 ms/1.3 ms/55°) allowed for localization of the heart in the three standard planes (transversal, sagittal, and coronal). Subsequently, a cine-scan with transversal slice orientation (SSFP, retrospective gating, 40 phases/cardiac cycle) was performed to automatically determine the individual cardiac rest period.14 Briefly, the cross-correlations between consecutive heart-phases were calculated automatically and displayed in a graph. The maxima of the correlation curve corresponded to the most quiescent heart-phases and defined the cardiac rest period (equal to optimal acquisition window) given in milliseconds.

Then, a calibration scan was performed for automatic adaptation of a navigator-driven affine respiratory motion model to the specific patient. An ECG-triggered multislice two-dimensional fast gradient echo sequence with a fat saturation and a T2-preparation pulse was used to acquire a series of 30 low-resolution three-dimensional data sets registering the breathing-related motion of the heart over several respiratory cycles.12,16 Two pencil-beam navigators characterized the current motion state: the first navigator was placed on the dome of the right hemidiaphragm to detect the liver–lung interface during free-breathing (equal to cranio-caudal component). The second navigator was placed on the right anterior chest wall (equal to anterior–posterior component) (Figure 1). The time series of three-dimensional image data sets were registered using a three-dimensional affine transformation comprising translational, rotational, scale, and shear motions. To derive the motion model, the resulting affine motion parameters were linked to the navigator data employing a principal component analysis.16 During the following MRCA sequence, the actual navigator displacements were fed into the previously determined motion model to predict and prospectively correct the breathing-related motion of the heart.

Immediately after the calibration scan, MRCA of the entire coronary arterial tree was performed with the earlier-mentioned motion correction algorithm employed. A sufficient number of strictly transversal slices (120–170) were obtained to cover the whole heart (SSFP sequence with a fat suppression and a T2 preparation pre-pulse;17,18 TR/TE/flip angle: 5.1 ms/2.3 ms/90°). Spatial resolution was nearly isotropic (in-plane 1.2 × 1.2 mm², slice thickness 1.4 mm). The acquisition duration per heart beat was set to the previously defined individual cardiac rest period and the gating window of the cranio-caudal navigator was set to 10 mm.

Figure 1 Planning procedure of calibration and MRCA scan: one navigator was positioned on the dome of the right hemidiaphragm and the liver–lung interface during free-breathing was detected. The corresponding navigator display showed the breathing-related motion in cranio-caudal direction. The second navigator was placed on the right anterior chest wall and the corresponding navigator display showed the breathing-related motion in anterior–posterior direction. The red volume covering the entire heart marked the three-dimensional volume being used for the MRCA sequence. See the online supplementary material for a colour version of this figure.
Navigator efficiency was defined as the number of accepted navigator-gated acquisitions divided by the total number of navigator acquisitions (values are given in per cent). A diagram of the MR imaging procedure is shown in Figure 2.

**Image analysis**

A visual score was used to grade the visibility of the coronary vessels: (i) poor/uninterpretable (coronary artery visible with markedly blurred borders); (ii) good (coronary artery visible with moderately blurred borders); (iii) very good (coronary artery visible with mildly blurred borders); (iv) excellent (coronary artery visible with sharply defined borders). For objective assessment of vessel sharpness, a previously published dedicated quantitative coronary analysis tool with an edge detection and vessel sharpness algorithm was applied on the raw data. Vessel sharpness was defined as the average signal along the vessel border on the edge image with higher values identifying better vessel delineation. The values were determined for the first 4 cm of the proximal segments of the left anterior descending artery (LAD), left circumflex artery (LCX), and right coronary artery (RCA). For quantification of angiographic parameters and visualization of coronary artery anatomy, multiplanar reformatting of the three-dimensional data set was carried out with the same software facilitating the measurement of vessel length and maximal luminal diameter as well as assessment of the number of visible side branches.

**Diagnostic performance**

For the assessment of coronary artery stenoses, the unprocessed raw data were used. To determine the diagnostic performance of the new MRCA approach, two different coronary segment models were applied: first, a 16-segment model according to the 29-segment model of the AHA/ACC guidelines and secondly, a 7-segment model, which had been used in a previously performed multicentre trial. For the 16-segment model, the following segments of the coronary arteries were evaluated: (i) left main segment, (ii) proximal segment of LAD, (iii) mid-segment of LAD, (iv) distal segment of LAD, (v) first diagonal branch, (vi) second diagonal branch, (vii) proximal segment of LCX, (viii) mid-segment of LCX, (ix) distal segment of LCX, (x) first marginal branch, (xi) second marginal branch, (xii) proximal segment of RCA, (xiii) mid-segment of RCA, (xiv) distal segment of RCA, (xv) right posterolateralis segment, and (xvi) posterolateralis descending artery segment.

For the 7-segment model, the following segments were evaluated: the left main coronary artery and proximal and mid-segments of the LAD (0–2 cm and 2–4 cm), the LCX (0–1.5 cm and 1.5–3 cm), and the RCA (0–2 cm and 2–5 cm). For both models, the coronary artery segments were classified as evaluable or impossible to evaluate, with the latter referring to non-visibility of the respective coronary segment; these segments were not considered for diagnosis. Visual assessment of stenosis detection was done in the remaining coronary artery segments; these were classified as having significant stenosis (i.e. ≥50% diameter reduction) or occlusion or showing the absence of a significant stenosis. A segmental reduction or signal loss in the MR image was considered to be indicative of a significant coronary artery stenosis or occlusion. The analysis of the MR coronary angiograms was performed by the consensus of two observers being fully blinded to the results of invasive coronary angiography.

**Invasive coronary angiography**

All coronary X-ray angiographies were performed within 3 weeks after MRCA using the transfemoral Judkins approach with a selective catheterization of the left and right coronary artery system in multiple projections. An experienced interventionalist blinded to the results of the MR examinations visually evaluated the angiograms. A significant coronary stenosis was defined as ≥50% luminal diameter narrowing.

**Statistical analysis**

Statistical analysis was performed using SPSS 11.5.1 for Windows (SPSS Inc.). For all continuous parameters mean ± SD are given. Sensitivity, specificity, and diagnostic accuracy were calculated according to standard definitions.

**Results**

**Feasibility**

**Scan parameters**

Patients characteristics are given in Table 1. The average number of slices needed to cover the whole heart was $137±9$ (range: 120–160 slices). Nominal scan duration of the MRCA sequence was $637±121$ s. The effective scan duration showed a wide range of variability ($9\ min\ 57\ s$ to $32\ min\ 42\ s$) depending on the respective navigator efficiency of the individual patient (Table 2).
MR angiographic parameters
All 20 MRCA examinations could be evaluated and at least the proximal and mid-segments of the three main vessels were considered excellently visualized in all patients. The left main segment in one patient was not imaged because of incorrect planning of the three-dimensional MRCA volume. Overall visual score and the quantitative MR angiographic parameters of the three coronary vessels are given in Table 3. Imaging examples are shown in Figures 3 and 4.

Diagnostic performance
Scan parameters
Patients characteristics are given in Table 1. The average number of slices needed to cover the whole heart was 138 ± 10 (range: 120–170 slices). Nominal scan duration of the MRCA sequence was 718 ± 137 s. The effective scan duration showed a wide range of variability (8 min 35 s to 29 min 46 s) depending on individual navigator efficiencies (Table 2).

MR angiographic parameters
In 32 out of 35 patients, MRCA yielded good-to-excellent image quality and was considered to be diagnostic. Three patients had to be excluded from further analysis because of incomplete MRCA data acquisition resulting from an unfavourable breathing pattern (n = 2) or patient movement (n = 1). Visual score and quantitative angiographic parameters of the three coronary vessels are provided in Table 3.

Invasive coronary angiography
Sixteen out of 32 patients (50%) had significant coronary artery disease; the number of patients with single-, double-, and triple-vessel disease was two (6%), five (16%), and nine (28%), respectively.

Diagnostic performance of coronary MRA
16-segment model. In the 32 patients, 88 out of 512 coronary artery segments (17%) had to be excluded from further analysis: 86 segments owing to poor image quality and two segments owing to incorrect planning (two left main segments). In the remaining 424 segments, 43 out of 55 significant coronary artery stenoses were correctly identified and in 337 of 369 segments, the absence of significant stenoses was correctly diagnosed (examples of reconstructed images in Figures 3 and 5). Calculation of sensitivity, specificity, and diagnostic accuracy resulted in 78, 91, and 89%, respectively (Table 4).

7-segment model. On the basis of the previously described 7-segment model, 99% of the coronary segments (222 out of 224) could be evaluated with the two missing segments representing the two left main segments which were not imaged because of incorrect planning. Twenty-seven out of 33 significant coronary artery stenoses were correctly identified and in 167 of 189 segments, the absence of significant stenoses was correctly diagnosed. Sensitivity, specificity, and diagnostic accuracy were 82, 88, and 87%, respectively (Table 4).

Table 1 Patient demographics

<table>
<thead>
<tr>
<th>Diagnostic performance (n = 32)</th>
<th>LAD</th>
<th>LCX</th>
<th>RCA</th>
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<tr>
<td>Feasibility (n = 20)</td>
<td></td>
<td></td>
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<tr>
<td>Women:men (n)</td>
<td>7:25</td>
<td>59:10</td>
<td>56:12</td>
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<td>Age (years)</td>
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<td>158:186</td>
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<td>25.6:4.5</td>
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<td>Heart rate (1/min)</td>
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<tr>
<td>Range</td>
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<tr>
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<td>Sharpness (%)</td>
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<td>44:7</td>
<td>44:7</td>
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<tr>
<td>Side branches</td>
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<td>1.8:0.7</td>
<td>2.3:0.9</td>
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<td>68:20</td>
<td>140:42</td>
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<td>Heart rate (1/min)</td>
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<tr>
<td>Range</td>
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<tr>
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<td>2.6:1.1</td>
<td>3.2:0.8</td>
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<td>2.6:0.4</td>
<td>2.2:0.4</td>
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<tr>
<td>Side branches</td>
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<td>1.3:0.5</td>
<td>2.4:0.9</td>
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<tr>
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<td>66:11</td>
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<td>Sharpness (%)</td>
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<td>38:7</td>
<td>46:8</td>
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Table 2 Scan characteristics of the patients

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<th>Navigator efficiency (%)</th>
<th>Scan duration nominal (min)</th>
<th>Scan duration effective (min)</th>
<th>Acquisition duration per heart beat (ms)</th>
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<td>Feasibility (n = 20)</td>
<td>67:15</td>
<td>11:2</td>
<td>17:6</td>
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<tr>
<td>Diagnostic performance (n = 32)</td>
<td>68:13</td>
<td>12:2</td>
<td>18:5</td>
</tr>
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</table>
Discussion

The present study offers a new approach for coronary MR angiography. SSFP sequences with an inherently high blood-pool signal were combined with a sophisticated and newly developed navigator technique for compensation of respiratory motion.

The feasibility of this MRCA approach could be demonstrated in a pilot study: high quality MRCA imaging could be performed in all patients as shown by visual assessment and objective, quantitative parameters of image quality. In addition, the diagnostic performance was assessed in patients with invasive angiography as the reference standard yielded excellent results in comparison with previously published MRCA studies: applying a 16-segment model, 83% of all coronary segments could be evaluated and sensitivity, specificity, and diagnostic accuracy were 78, 91, and 89%, respectively. Using the previously suggested 7-segment model, 99% of the coronary segments were evaluable and sensitivity, specificity, and diagnostic accuracy were 82, 88, and 87%, respectively.

For application of MRCA in clinical routine, the imaging approach needs to fulfill the following requirements: reliable visualization of the whole coronary arterial tree including distal segments and side branches and reliable detection of coronary artery stenoses within a short total examination duration. Thus, optimal compensation of coronary motion due to respiratory or cardiac movement plays a pivotal role in minimizing blurring and ensuring complete freezing of the coronary vessels. A high and isotropic spatial resolution would allow visualization of small diameter vessels and assessment of non-distorted luminal coronary dimensions.

However, the higher the spatial resolution and the shorter the acquisition window (needed to ensure coronary freezing), the longer the total scan duration. Prolonged total duration of MRCA usually leads to a decreased navigator efficiency, e.g. owing to diaphragmatic drift or patient movement. Consequently, a clinically applicable MRCA routine protocol needs to combine optimized motion compensation techniques with high resolution imaging, yet, still ensuring an acceptable total examination duration.

In our study, we combined the whole-heart approach described by Weber et al.6 with an affine respiratory motion correction technique: the acquisition of a large three-dimensional volume covering the complete heart...

Figure 3 Multiplanar reformatted MR images (‘soap bubble’ visualization) of the left coronary artery system. (A) MRCA of two different patients of the feasibility subgroup. Please note the excellent visualization of LAD and LCX including distal segments and major side branches. (B) MRCA of a patient with double-vessel disease (diagnostic performance subgroup). Stenoses of the LAD and LCX are shown (solid arrows). X-ray angiography confirmed these findings. Ao, aorta.

Figure 4 Three-dimensional volume rendering of the whole coronary arterial tree of two different patients (panel A and B) of subgroup 1. The high signal- and contrast-to-noise ratio together with an excellent vessel border definition enabled segmentation and three-dimensional reconstruction of the coronary tree with interactive visualization in any desired angulation. The representative examples in panel A and B show the standard views for the LCA and RCA as known from invasive X-ray angiography: there is an excellent visualization of the three main vessels including distal parts and side branches. See online supplementary files: three-dimensional MRCA reconstruction of the patient in panel A (movie 4a-1 and 4a-2), with movie 4a-2 exemplifying the reconstruction using a software algorithm for whole-heart visualization as known from computed tomography. See online supplementary material for a colour version of this figure.
abandoned the need for time-consuming and complicated planning and thus shortened total examination duration. However, in three patients, the left main segment was not visualized because of inadequate planning of the transversal volume. The reason for this was that the scout images were acquired during an expiratory breath-hold, whereas the coronary scan was performed during free-breathing, resulting in a slightly different position of the heart. Thus, we recommend to perform a low-resolution coronary scout scan during free-breathing to ensure optimal positioning of the three-dimensional volume. In addition, a relevant shortening of the coronary sequence duration was achieved resulting from the application of the affine transformation algorithm for respiratory motion compensation, which allowed to extend the navigator-gating window from the conventionally used 5 mm to 10 mm and a concomitant increase in navigator efficiency (68% on average).

For comparison with previously reported data, we applied the identical 7-segment model to our MRCA data: in the present study, diagnostic performance was found to be higher, especially with regard to specificity (88 vs. 73%). In general, false-positive results have been mainly related to signal disturbances arising from flow alterations within the coronary lumen, which can cause misinterpretation of the coronary lumen as being narrowed. In the present study, the reduction in the number of false-positive results was most likely related to (i) the more favourable, flow-independent signal intensity characteristics of SSFP sequences leading to an improved vessel border definition and (ii) the optimized motion compensation used to minimize vessel blurring. Thus, the combination of flow-independent signal reception from the coronary lumen together with complete freezing of coronary motion is essential and reduces the eventual occurrence of a luminal signal loss, which may be misinterpreted as a significant coronary artery stenosis or occlusion. Moreover, in the present study, the number of evaluable segments was higher in comparison with Kim et al. (99 vs. 84%) mainly because of the overall improved image quality.

**Conclusion**

Coverage of the entire coronary arterial tree during a single MR measurement and application of an affine transformation algorithm for respiratory motion compensation allowed the reliable visualization of the whole coronary arterial tree. This new MRCA approach yielded a high diagnostic performance with regard to stenosis detection with conventional X-ray angiography as the standard of reference and an increased number of coronary segments were evaluable. The proposed MRCA approach was performed without time-consuming planning procedures and within a reasonably short total examination duration. Thus, robustness and diagnostic accuracy may allow for a routine application of non-invasive coronary MR imaging in the near future.

**Supplementary material**

Supplementary material is available from *European Heart Journal* online.

**Acknowledgement**

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