Magnetic Resonance–Guided Coronary Artery Stent Placement in a Swine Model

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Background—Magnetic resonance (MR)–guided coronary artery stent placement is a challenging vascular intervention because of the small size of the coronary arteries combined with incessant motion during the respiratory and cardiac cycles. These obstacles necessitate higher temporal and higher spatial resolution real-time MR imaging techniques when compared with interventional peripheral MR angiography.

Methods and Results—A new, ultrafast, real-time MR imaging technique that combines steady-state free precession (SSFP) for high signal-to-noise ratio and radial k-space sampling (rSSFP) for motion artifact suppression was implemented on a 1.5-T clinical whole-body interventional MR scanner. The sliding window reconstruction technique yielded a frame rate of 15/s allowing for data acquisition during free breathing and without cardiac triggering. Eleven balloon-expandable stainless steel coronary stents were placed in both coronary arteries of 7 pigs (40 to 70 kg body weight) using a nitinol guidewire and passive device visualization. Position of the coronary stents was controlled by a navigator-gated free-breathing ECG–triggered three-dimensional SSFP coronary MRA sequence and confirmed visually on the ex vivo heart. The presented real-time MR imaging sequence reliably allowed for high-quality coronary MR fluoroscopy without motion artifacts in all pigs. Ten of 11 coronary stents were correctly placed under MR guidance. One stent dislodged proximally from the left main coronary artery because of too-small balloon size. Stent dislocation was correctly predicted during real-time MR imaging.

Conclusion—The presented approach allows for real-time MR-guided coronary artery stent placement in a swine model. (Circulation. 2002;105:874-879.)

Key Words: magnetic resonance imaging ■ coronary disease ■ stents

Over the last decade, coronary stents have emerged as the most common percutaneous therapy for focal coronary artery stenoses.1-3 During stent placement, x-ray coronary angiography is used both for the detection of the coronary lesion and for the guidance of stent deployment. However, x-ray angiography with iodinated dye injection only displays the coronary artery lumen and may therefore underestimate the presence of soft plaques associated with minimal or no lumen narrowing.4 Recently, coronary magnetic resonance angiography (MRA) including three-dimensional (3D) visualization has been used to identify coronary artery stenoses.5,6 Furthermore, MR imaging allows for the assessment of myocardial viability7 and coronary artery vessel wall/plaque morphology,5,9 thereby providing important information, which may lead to modification of a stent placement procedure such as inclusion of soft plaques.4 The combination of MR plaque information with interventional MR-guided coronary stent placement may provide a favorable clinical potential. In contrast to MR-guided stent placement in peripheral arteries,10,11 coronary MR-guided interventions must accommodate the substantial motion artifacts originating from the respiratory and the cardiac cycles.12 In addition, MR-guided coronary artery interventions are especially challenging because of the small size and the tortuous anatomy of the coronary vessels.13 Real-time imaging with high spatial resolution and interactive slice positioning are prerequisites for MR-guided coronary interventions. The aim of this work was to explore the potential of a newly developed, motion-insensitive, interactive real-time radial steady-state free precession (rSSFP) MR imaging sequence to guide coronary artery stent placement. Such an approach could extend the attributes of coronary MRA to include both diagnosis and guided intervention of coronary artery disease.

Materials and Methods

MR Imaging System

All studies were performed on a clinical 1.5-T short-bore (60 cm gantry diameter and 68 cm central gantry length) whole-body
interventional MR scanner (ACS-NT, Philips Medical Systems), which allows for access to the probe inside the scanner for vascular interventions. The system is equipped with a dedicated real-time reconstruction system and online image display at the magnet. For signal reception, a five-element commercial cardiac synergy coil was used.

Fast Navigator-Gated Free-Breathing 3D SSFP Coronary MRA

For anatomic display of the coronary arteries before and during stent placement, a fast navigator-gated free-breathing segmented k-space cardiac-triggered 3D SSFP coronary MRA sequence (TR 3.9 ms/TE 1.9 ms, flip angle 75°, and 1.2×1.2×1.5 mm³ voxel size) was used. Image acquisition was timed to late diastole using an animal-specific trigger delay to avoid cardiac motion artifacts. Because steady-state conditions are important for maximized contrast and optimized image quality in SSFP imaging, 20 startup cycles preceded each diastolic imaging acquisition interval (25 excitation/R-R interval) to achieve a steady-state condition for each segment. Data were acquired during free breathing (mechanical ventilation) utilizing a prospective right hemidiaphragmatic real-time navigator for respiratory motion artifact suppression. On the basis of a first transverse orientation, double-oblique slice orientations of the 3D SSFP coronary MRA (16 slices) were performed in parallel to the right and left descending coronary artery, respectively, using a three-point planar scan tool. The anatomic display of the coronary artery anatomy derived from these scans was used for planning of the subsequent real-time imaging planes. Measurement time including navigator gating was less than 2 minutes per sequence.

Interactive Real-Time MR Imaging Sequence

MR-guided stent placement was performed using a newly developed interactive real-time rSSFP imaging sequence (TR 2.5 ms/TE 1.2 ms, flip angle 45°, 80 radials, 128×128 matrix, reconstruction to 256×256 pixels, and 300 mm field of view) during free breathing and without cardiac triggering. Image reconstruction was performed using the sliding window technique allowing for enhanced temporal resolution and thereby facilitating real-time images with a frame rate of 15/s that were displayed online on a liquid crystal diode screen at the magnet. Image slice position, orientation, and contrast parameters could be changed interactively. Imaging position was adjusted using the anatomic display of the coronary artery tree as derived from the fast 3D SSFP coronary MRA sequence to visualize the longest course of the coronary artery.

Animal Preparation and Experimental Protocol

Before in vivo studies, visualization of the stainless steel stent (Flex Force Coronary Stent, Aachen Resonance) with the fast 3D SSFP coronary MRA and interactive real-time rSSFP sequence was investigated in a water bath (Figure 1). Animal experiments were performed in seven domestic swine (40 to 70 kg body weight) as approved by the government committee on animal investigations. After premedication with 0.5 mL IM atropine and 0.2 mL IM azaperone/kg body weight, an aqueous solution of pentobarbital (1:3) was administered intravenously through an ear vein as needed. The animals were intubated and mechanical ventilation was maintained throughout the intervention. A 9F sheath (Cordis) was placed surgically in the right carotid artery.

On the basis of the double-oblique 3D SSFP sequence described above, three additional slice orientations for the different steps of coronary intervention were defined interactively, as follows. For catheter placement in the aortic bulb, a parasagittal slice orientation showing the right common carotid artery and the aortic arch was chosen (Figure 2). A second slice orientation was oriented through the ascending aorta and both coronary artery origins. A third imaging plane was defined through the ascending aorta; the right or left coronary artery origin; and the proximal/middle portion of the right coronary artery, left anterior descending artery (LAD), or right circumflex artery (RCX). On the basis of these imaging planes, real-time MR imaging and control of the coronary intervention was performed.

A commercial Flex Force stainless steel coronary stent (2.5 to 5 mm diameter, 1.5 cm length, and 0.09 mm wall thickness) was mounted on either a 4-mm (n=6, Smash, Boston Scientific) or a 3-mm (n=5, Invatec) balloon catheter. As no MR-compatible guiding catheter was available, catheter tips were bent to facilitate coronary ostium engagement. The coronary artery lumen was displayed, signal enhanced, without contrast media while nitinol guidewires (0.018 inches for 3-mm balloons or 0.035 inches for 4-mm balloons, Terumo) as well as the mounted stent displayed signal attenuation using passive visualization (Figure 1). This allowed for coronary artery lumen and device visualization for coronary artery catheterization using an access from the pig’s right carotic artery.

Stent Placement Procedure

The guidewire tip and the mounted stent were placed under MR fluoroscopy into the aortic bulb. Subsequently, the guidewire was engaged in the left or right coronary artery. On the basis of the previously defined imaging planes, the user moved interactively through variable slice positions and orientations to ensure constant device visualization. Finally, the mounted stent was placed in the user-specified portion of the coronary artery as defined on the 3D coronary MRA images (right proximal coronary artery [n=3], left proximal descending coronary artery [n=3], middle portion of the left descending coronary artery [n=2], proximal left circumflex [n=1], and left main artery [n=2]) and deployed by inflating the balloon with saline solution. Stent localization on the real-time images was visually compared with the baseline fast 3D SSFP coronary MRA sequence to ensure correct placement in the user-
specified portion of the coronary arteries. Furthermore, before and after balloon inflation, the fast 3D SSFP sequence was performed to control the correct stent localization as seen by real-time MR. After MR-guided stent placement, the heart was excised and the anatomic position of the stent visually confirmed.

**Results**

**Navigator-Gated Free-Breathing 3D SSFP Coronary MRA**

In all animals, right and left coronary arteries were successfully visualized in subject-specific adopted double-oblique slice orientations using the fast 3D SSFP coronary MRA sequence (Figure 3). The coronary artery lumen was displayed with a high signal intensity and high contrast to the surrounding tissue, with minimal motion artifact. The crimped and deployed stents were successfully visualized on the 3D SSFP images with a signal void slightly larger than the coronary artery lumen diameter (Figures 4 and 5), whereas the utilized nitinol guidewires demonstrated a smaller artifact (Figure 4) consistent with in vitro findings (Figure 1).

**Interactive Real-Time MR Imaging Sequence and Stent Placement Procedure**

On the basis of the double-oblique 3D SSFP coronary MRA images, all three imaging planes for monitoring of coronary intervention were easily defined in all pigs, exploiting interactive planning during real-time imaging (Figure 2). The aorta, coronary ostium, and proximal and middle portion of the coronary artery could be successfully visualized with the real-time rSSFP imaging sequence. Motion artifacts were suppressed (Figure 2). Similar to the 3D SSFP coronary MRA images, both nitinol guidewires used displayed a relatively small artifact, whereas the mounted stent resulted in a larger artifact allowing for stent localization (Figures 1, 6, and 7). The coronary artery lumen was displayed with a high signal except for the region of the stent (Figures 6 and 7). Movement of the stent along the carotid artery and the aorta, in the coronary origin, and in the proximal and middle portions of the coronary arteries could be well controlled in real time (Figures 6 and 7). However, because of the small artifact of the guidewires used as well as the tortuous course of the coronary arteries, the guidewire tip could not be consistently visualized.

In 10 (91%) cases, the final stent localization as depicted on the real-time rSSFP images was similar to that displayed by the 3D SSFP images and an autopsy. One stent deployed in the left main coronary artery of the largest pig (70 kg body weight) was not visible on the real-time rSSFP images immediately after balloon deflation. The 3D SSFP scan also failed to image the stent in the left main coronary artery. At autopsy, the stent was noted to be dislodged proximally along the guidewire.
After planning of the slice orientations for coronary artery intervention, the total MR fluoroscopy time for a single stent placement (without the intervening 3D SSFP coronary MRA scans) ranged from 4 to 18 minutes.

Discussion
The feasibility of MR-guided peripheral stent placement was recently demonstrated in animals and patients.10,11 To our knowledge, the current report represents the first MR-guided coronary artery stent placement. Improved gradient performance, ultrafast reconstruction capabilities,14 and recently developed software tools for “on-the-fly” interactive MR scanning18 now offer the potential for real-time MR imaging with sufficient contrast and spatial resolution for MR-guided coronary interventions.

Interactive Real-Time MR Imaging Sequence
The small-diameter, tortuous anatomy and the extensive motion of the coronary arteries in the cardiac and respiratory cycles make MR-guided coronary interventions technically demanding. Using an rSSFP approach, visualization of thoracic anatomy, coronary artery origins, and more distal coronary artery lumen as well as the interventional device was successfully performed using subject-specific slice orientations for each step of the intervention (catheter placement in the aortic sinus, catheterization of the coronary artery, and stent placement). This was accomplished using an interactive tool18 that enabled real-time adjustment of image orientations, thereby facilitating real-time monitoring of the coronary artery intervention.

The main improvement for sufficient coronary MR fluoroscopy was the newly developed rSSFP real-time imaging sequence. Because of the basic MR physics, spatial resolution always has to be balanced against temporal resolution. The inherent high signal-to-noise ratio of SSFP19–21 allowed for real-time acquisition of images with a high spatial resolution. Furthermore, SSFP MR fluoroscopy demonstrated a high contrast of the coronary artery lumen without injection of an exogenous contrast agent. For this sequence, contrast is based on the “T2-like” contrast rather than inflow of unsaturated protons,20,21 which may partially explain the excellent visibility of coronary artery lumen even directly adjacent to the interventional device. Enhanced motion artifact suppression was realized by combination of the real-time data acquisition with radial k-space filling, the latter offering superior motion artifact suppression when compared with cartesian readouts.10,22,23 An additional advantage of radial k-space filling is an option for undersampling of radials, thereby further enhancing temporal resolution without sacrificing spatial resolution.24 Therefore, in contrast to cartesian k-space filling, the radial acquisition spatial resolution is not negatively affected by time-saving undersampling. In addition, improved temporal resolution was achieved applying the sliding window technique.17 The combination allowed for high-quality coronary MRA fluoroscopy for coronary artery localization and stent placement. Coronary interventions were completed in a reasonable (4- to 18-minute) time period. Motion artifacts were suppressed while instrumentation motion could be sufficiently visualized, a characteristic of radial sequences.10 With the present approach, no exogenous contrast agent was needed.

Fast Navigator-Gated Free-Breathing 3D SSFP Scan
For 3D visualization of the coronary artery anatomy as well as for planning and control of MR-guided coronary stent placement, we utilized a fast navigator-gated, free-breathing 3D MR-guided coronary MRA scan. This sequence consisted of a thick transverse or double-oblique 3D imaging slab oriented along the major axis of the coronary arteries and allowed for a fast 3D update of coronary artery visualization. Such a fast sequence can also be used as an additional control to real-time imaging for each interventional step such as guidewire or mounted stent placement. In contrast to two-dimensional real-time imaging, the 3D SSFP coronary MRA imaging slab allowed for the visualization of adjacent slices to the real-time imaging plane and thereby complete coronary artery display, allowing for more precise stent localization.
The 3D SSFP coronary MRA scan had a 1.2-mm inplane resolution and enabled coronary artery lumen and coronary stent visualization in less than 2 minutes using navigator gating. For diagnostic imaging of the coronary arteries, higher-resolution scans may be needed.\textsuperscript{5,6} However, total scan time of this technique is typically longer than 10 minutes, making such an approach impractical for use during a coronary intervention. Acquisition speed for 3D SSFP coronary MRA may be enhanced using parallel imaging techniques.\textsuperscript{25}

**General Findings and Clinical Implications of MR-Guided Coronary Artery Stent Placement**

With the presented interactive real-time rSSFP imaging sequence, 10 of 11 stents were successfully deployed in the user-defined portion of the right or left coronary artery as specified on the 3D SSFP coronary MRA. One stent dislodged after placement in the left main coronary artery, a finding that was detected on real-time imaging and confirmed by both 3D SSFP coronary MRA and at autopsy. The likely cause for stent dislocation in this case was a geometric mismatch between the 4 mm balloon size and the size of the left main coronary artery origin (which was determined to be 4.8 mm on subsequent offline measurements\textsuperscript{6}). More precise, automatic diameter measurements may prevent such occurrences. Although stent displacement was detected, other potential complications, including coronary artery dissection and acute stent thrombosis,\textsuperscript{26} remain to be demonstrated using this approach.

In our study, coronary stent placement was performed in healthy animals. For clinical MR-guided coronary stent placement, focal coronary artery stenoses must be localized on the real-time images. In this first study, no animals with atherosclerotic lesions were studied because of our concern regarding potential complications during the intervention. The presented results warrant further investigations to define the potential of the presented real-time and fast 3D SSFP coronary MRA technique to visualize coronary artery stenosis and to treat coronary artery stenosis using MR-guided coronary artery stent placement. Furthermore, objective measurements of the accuracy of MR-guided coronary stent placement and demonstration of full stent expansion remain to be compared with x-ray angiography.

We chose passive visualization of the guidewire and stent on the basis of visualization of the associated susceptibility artifacts in the MR image.\textsuperscript{27,28} Passive visualization can be easily performed on standard MR scanners without additional hardware. Stainless steel stents cause a susceptibility artifact, which is large enough for easy passive stent detection without obscuring major parts of the anatomy. An alternative to passive visualization may be active device visualization\textsuperscript{11,29–32} using microcoils at the catheter tip for calculation of its position. However, for clinical use, microcoil safety problems related to local heating must be resolved.\textsuperscript{28,33,34} First experiments for safe active tracking have been published, but miniaturization is needed before these techniques can be applied to the coronary arteries.\textsuperscript{28,35,36} According to our experience, active visualization is necessary to allow accurate device localization in the more distal portions of the coronary arteries, where our passive visualization approach was of limited value. For example, it was not reliably possible to visualize the guidewire tip in the distal coronary arteries. However, this is required for a safe interventional procedure, and this limitation impeded visualization of branch instead of distal main vessel catheterization.

In comparison with x-ray angiography, which exclusively displays the coronary artery lumen displaced by the radiographic contrast agent, MR imaging allows for continuous visualization of coronary artery and surrounding tissues without an exogenous contrast agent and therefore without additional guiding catheters. Furthermore, MR does not expose the patient or medical personnel to potentially harmful ionizing radiation. Although not explored in this study, MR imaging allows for coronary vessel wall and plaque visualization.\textsuperscript{8,9} This information may enable improved strategies for treatment of soft plaques in the absence of a significant luminal narrowing. The addition of interventional MR to diagnostic coronary MRA may lead to the emergence of MR as a unified tool for the diagnosis and treatment of coronary artery disease.

**Conclusions**

Interactive real-time rSSFP is a promising new tool for coronary MR fluoroscopy, allowing MR-guided coronary artery stent placement in a swine model.

**References**


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