Real-Time Magnetic Resonance Imaging-Guided Coronary Catheterization in Swine

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Background—We tested the hypothesis that real-time magnetic resonance imaging (MRI) can guide coronary artery catheterization in swine via a percutaneous femoral artery approach.

Methods and Results—In 12 pigs, we accessed femoral arteries percutaneously. We used 6- or 7-French coronary Judkins catheters filled with dilute 4% gadolinium (Gd) contrast agent and coaxially inserted 0.030-inch diameter active guidewires as endovascular devices. For catheter tracking, we used a 2-dimensional (2D) inversion recovery–prepared spoiled gradient echo sequence at a temporal resolution of 7 frames/s. For guidewire tracking, we used 2D steady-state free precession imaging at a temporal resolution of 9 frames/s. Coronary artery catheterization under MRI guidance was successful in 12/12 pigs. Successful coronary catheterization was verified by obtaining MR angiographic images after direct catheter-based injections of dilute Gd.

Conclusions—Real-time MRI-guided catheterization of coronary arteries in swine is feasible via a percutaneous femoral artery approach. Selective coronary MR angiography can then be performed with dilute contrast agent injections. (Circulation. 2003;107:2656-2659.)

Key Words: magnetic resonance imaging ▪ catheterization ▪ arteries ▪ angiography

Magnetic resonance imaging (MRI) guidance for diagnostic and therapeutic endovascular procedures has several potential advantages over conventional x-ray guidance. Compared with x-ray guidance, MRI (1) avoids ionizing radiation exposure; (2) limits potential nephrotoxic effects and allergic reactions of iodinated contrast agents; (3) provides 3-dimensional anatomic information; and (4) has the ability to measure changes in end-organ function. Catheter-based coronary MR angiography (MRA) is feasible using dilute contrast agent injections.1 However, MRI-guided catheterization of the coronary arteries is difficult because limited signal detection constrains spatial and temporal resolution for device tracking. An active internal guidewire used in conjunction with a contrast agent-filled catheter is one approach2 to improve signal detection of endovascular devices. Using this approach, we tested the hypothesis that MRI can successfully guide real-time coronary catheterization in swine.

Methods

Our institution’s Animal Care and Use Committee approved all animal experiments. We performed experiments in 12 healthy domestic female swine (22 to 35 kg; Oak Hill Genetics, Ewing, Ill). After endotracheal intubation, they received inhaled isoflurane during mechanical ventilation. In our animal laboratory, sonography was used to guide percutaneous common femoral artery puncture.

After placing 6- to 8-French vascular sheaths under x-ray guidance, we administered intravenous heparin 5000 U. Preliminary coronary x-ray angiography was performed with a Judkins catheter (curve sizes 2.5 to 3.5) and the catheter was removed. We then transferred the animals to a 1.5 T MRI scanner (Sonata, Siemens) for subsequent experiments.

For real-time catheter tracking, we used an 80-cm length 6- or 7-French Judkins coronary catheter (Cook) and a coaxially inserted active guidewire (Intercept, Surgi-Vision). The residual annular lumen of the catheter was filled with 4% gadolinium (Gd) contrast agent (Prohance, Bracco). T1-shortening by the dilute contrast agent allowed direct visualization of the catheter lumen as bright signal.3 The 100-cm long active guidewire, containing a loopless antenna mounted on 0.030-inch diameter nitinol, functioned as an internal radiofrequency (RF) receiver coil.4 The active guidewire significantly increases signal detection within the catheter lumen but has a sharp and highly localized sensitivity profile along the length of the guidewire. A rotating hemostatic valve adaptor was attached to the catheter and guidewire to prevent leakage of contrast agent. We tracked the catheter using a 2-dimensional (2D) inversion recovery (IR)–prepared fast low angle shot (FLASH) spoiled gradient echo sequence.5 Typical scan parameters were as follows: repetition time (TR)/echo time (TE)/flip angle=2.3 ms/1.15 ms/20°; inversion time (TI)=50 ms; field of view (FOV)=206×300 mm²; acquisition matrix=74×256; slice thickness=30 mm. Using a sliding window technique,6 42 new lines were acquired each acquisition period, yielding effective temporal resolution of 7 frames/s.

For direct guidewire visualization, we used 2D fast imaging with steady-state precession (TrueFISP). This pulse sequence directly
detects the nitinol active guidewire as negative susceptibility artifact. However, the internal RF coil enhances guidewire visualization by depicting adjacent surrounding tissues as bright signal. The external phased array coil was used to provide anatomical background. Typical scan parameters were as follows: TR/TE/flip angle = 2.9 ms/1.45 ms/70°, FOV = 206 x 300 mm²; matrix = 70 x 128; slice thickness = 30 mm. We implemented the same sliding window technique for TrueFISP, but acquired 40 new lines each acquisition period. This yielded effective temporal resolution of 9 frames/s.

To provide vascular roadmaps during catheter movements, we performed catheter-based intraarterial (IA) injections of 4% Gd contrast agent1,7,8 and collected images using the same 2D projection IR-FLASH sequence. We tailored IA injection rate and contrast agent volume to blood vessel caliber.

Under real-time MRI guidance, we advanced the active guidewire and catheter from the femoral artery into the left (n = 11) or right (n = 1) coronary arteries. Before device movement, we determined three oblique anatomic orientations and locations: sagittal for the aortic arch, coronal for the coronary ostium, and transverse for the proximal coronary arteries. We interactively selected the desired orientation/location based on device position.

Once the coronary ostium was engaged, we performed 2D projection coronary MRA using catheter-based injections of 3 to 16 mL of 4% to 8% Gd. An electrocardiographic-triggered, segmented IR-TrueFISP sequence was used. This coronary MRA was distinguished from roadmap acquisitions because of its longer imaging time (~4 seconds) and submillimeter in-plane spatial resolution (0.9 x 0.8 mm²).

Results
Figure 1 shows sample reference anatomic, guidewire tracking, and catheter tracking images during catheterization. The active guidewire was seen as susceptibility-induced signal void using TrueFISP. The active guidewire’s RF coil depicted surrounding tissue as bright, increasing the contrast between the guidewire and the background tissue. The dilute Gd-filled catheter was depicted as bright signal with completely suppressed background using IR-FLASH.

Coronary catheterization under MRI guidance was successful in 12/12 pigs. Only one coronary artery was catheterized and imaged per animal. During catheterization, the interventionalist viewed device movements on the imaging console adjacent to the MRI scanner. A separate MRI operator controlled imaging parameters as requested by the interventionalist. For catheter tracking, static reference images were placed next to real-time tracking images. During coronary artery manipulations, the internal coil remained within the catheter, with the guidewire tip located immediately proximal to the catheter end-hole. Engagement of the right coronary artery required gentle clockwise rotation of the external portion of the catheter. The operator assessed engagement through visual detection and tactile feedback.

Typical duration to engage the desired coronary artery was approximately 20 minutes. This time period began during MRI-guided insertion of the coronary catheter/guidewire combination through the existing femoral arterial sheath and ended once coronary roadmaps were obtained. No thrombus was detected within the arterial system or associated with the guidewire or catheter.

Vascular roadmaps were obtained using the same IR-FLASH sequence as for catheter tracking, except that the external coil was used instead of the guidewire coil. Higher spatial resolution catheter-based coronary MRA, in any projection, was also feasible. Figure 2 illustrates MR images, along with comparison x-ray angiography. In one pig, follow-up x-ray aortography and coronary angiography after MRI-guided coronary catheterization revealed no vascular injury related to the coil.

Discussion
In swine, we demonstrated the feasibility of real-time coronary catheterization under MRI guidance. We tracked the catheters and guidewires at 7 to 9 frames/s, while maintaining enough signal and spatial resolution for reproducible detection of each device. Once each coronary ostium was engaged,
we performed catheter-based coronary MRA by injecting dilute Gd.

Serfaty et al\(^1\) first performed 2D projection coronary MRA with injections of dilute Gd. They placed catheters in the coronary arteries under x-ray guidance with carotid access, rather than under MRI guidance and femoral access. Spuentrup et al\(^9\) used MRI to guide coronary artery stent placement in swine. In their study, the large metallic signal void of the stent was tracked rather than the catheter itself. Their surgical carotid access made catheterization much easier compared with a femoral artery approach due to the more direct and shorter route to the coronary ostium. Additionally, no catheter-based coronary roadmaps were acquired to verify catheter position. By using percutaneous femoral access and catheter-based injections of contrast agent, we more closely mimicked the clinical setting of x-ray guided coronary catheterization. We also consistently visualized catheter and guidewire movements.

The Gd-filled catheter/active guidewire technique\(^2\) used in this study combines several advantages of passive and active catheter tracking. The active guidewire improves signal detection of the Gd-filled catheter lumen. This increased sensitivity detects smaller diameter catheters at higher temporal resolutions than passive tracking methods.\(^3,5,10\) Unlike tracking techniques using active catheters,\(^11,12,13\) no special catheters are required with this combined approach.

Typical active guidewire tracking approaches have used spoiled gradient echo imaging.\(^4,14\) We prefer TrueFISP because it is more sensitive to susceptibility changes in the vicinity of the guidewire and thus allows more consistent depiction of the guidewire itself rather than just the surrounding tissue. The susceptibility effect permitted, rather than interfered with, guidewire visualization.

There were several important limitations to this study. First, we did not provide pathological assessment of potential valvular or vascular injury caused by the procedure. Second, active internal coils cause local tissue heating. However, the guidewire coil used in this study has been approved by the Food and Drug Administration for peripheral plaque imaging in humans. We attempted to minimize this heating by using a single internal coil as an active guidewire, rather than using two separate internal coils for separate guidewire and catheter tracking.\(^13\) Third, all animals underwent x-ray coronary angiography before MRI-guided coronary catheterization. This approach might have favorably influenced the success of MRI guidance. Finally, the spatial resolution of MRA is still insufficient to visualize stenosis in distal and branch arteries. Potential improvements in signal-to-noise ratio and spatial/temporal resolution are possible with higher imaging fields, intravascular coils, and technical advances such as echoplanar imaging, projection reconstruction, and parallel imaging. An alternative method to define coronary artery disease significance is to measure regional myocardial perfusion using MRI with local contrast injection.

Before clinical applications in humans, additional technical improvements and safety testing will be required. Catheterization of diseased human vessels will take longer and be more difficult than in the normal swine vessels tested in this study. Reductions in procedure time and further improvements in spatial resolution of coronary MRA will be essential before MRI-guided coronary interventions become clinically feasible.

**Conclusions**

MRI-guided catheterization of coronary arteries in swine is feasible in real-time. Use of the femoral artery approach represents a technical advance over previous studies. Selective coronary MRA can be performed with catheter-based injections of dilute contrast agent.

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**References**

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