MRI-Guided Coronary Catheterization and PTCA: A Feasibility Study on a Dog Model

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The aim of this work was to demonstrate the feasibility of MRI-guided coronary artery catheterization and intervention in a dog model. Experiments were performed on 10 healthy dogs. A 9F introducer sheath was placed through a right carotid artery cutdown. A prototype 0.014-inch coronary MRI guidewire, a prototype 7 French MRI-guiding catheter, and two flexible surface coils were connected to a GE 1.5 T CV/i scanner for simultaneous visualization of the guidewire, guiding catheter, and chest anatomy. Images were displayed in real time on an in-room monitor. A nongated, single-slice fast gradient-echo sequence was used to obtain real-time images of the catheters and background anatomy during the intervention. Fifteen selective catheterizations were attempted in the coronary arteries, and all were successful. Selective injection of diluted gadolinium into the MRI-guiding catheter provided dynamic 2D projection coronary angiography in all cases, confirming successful catheterization. Percutaneous transluminal coronary angioplasty (PTCA) was attempted after two catheterizations, and all attempts were successful. Inflation of the balloon angioplasty catheter was performed successfully in the left anterior and circumflex arteries. Our results indicate that coronary artery catheterization and intracoronary balloon angioplasty are feasible with MRI guidance only. MRI guidance may be used as an alternative to X-ray guidance in coronary artery interventions in the future. Magn Reson Med 49:258–263, 2003. © 2003 Wiley-Liss, Inc.

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The growth of percutaneous transluminal coronary angioplasty (PTCA) guided by X-ray fluoroscopy has been explosive over the last 10 years. Today, over 1 million PTCA interventions are performed each year worldwide for the treatment of angina and myocardial infarction. X-ray fluoroscopy allows real-time visualization of interventional devices and coronary vessels, and provides the ability to navigate, inflate balloons, and deliver stents in the coronary arteries. However, X-ray fluoroscopy is limited as an imaging technique for the study of anatomy, function, and perfusion of the heart. Furthermore, it cannot provide high-resolution or high-contrast imaging of the artery wall, which precludes the study of atherosclerotic plaque composition and the monitoring of local treatment delivery. MRI is a highly valuable technique for assessing the anatomy, physiology, and function of the heart (1) and its vessels (2–4). MRI is also sensitive to changes in temperature, and can be used to monitor heat-based therapies.

The introduction of fast image acquisition sequences during the last 10 years has led researchers to consider MRI as a potential tool for body interventions in general, and vascular interventions in particular. To reach this goal, development of visible guidewires (active guidewires) has been initiated (5–12) and real-time reconstruction systems have been produced. The simultaneous visualization of a guidewire, guiding catheter, and anatomy has been shown to be possible (13). Arteries can now be visualized in real time (14,15).

Previous reports (11,16–18) have described selective catheterization of large peripheral vessels with balloon angioplasty, and stent deployment procedures. We recently presented the first report of an MR-guided coronary artery catheterization and intervention (19), which is further detailed in this work.

Our first goal was to demonstrate that coronary artery catheterization, performed completely under MR guidance and using slice-selection techniques, can be accomplished in a very short period of time. The second goal was to show that a projection technique for coronary angiography and complete guidewire visualization can be used to position a balloon angioplasty catheter in a coronary artery, and thus could be used for treatment.

METHODS

MRI Guidewires and MRI-Guiding Catheters

The conventional design of an MRI receiver antenna consists of a loop geometry, and the antenna is placed outside the body. The loopless antenna is a coaxial cable with an extended inner conductor, which can be placed inside vessels (7). When connected to the scanner, the loopless antenna can provide images of the immediately adjacent tissues with a high signal, and can be detected on a body image as a bright line (20). Its geometry and high visibility in the body makes it a valuable tool for interventions that require an MRI-visible guidewire.

In collaboration with Surgi-Vision, Inc. (Columbia, MD), we developed a 0.014-inch prototype MRI guidewire (not commercially available) constructed of nitinol (Fig. 1) to achieve the flexibility and maneuverability necessary for coronary artery interventions. We also built a prototype 7-French MRI-guiding catheter (not commercially available) by attaching a 100-cm-long nitinol MRI guidewire (0.032 inch) to a conventional 100-cm-long guiding cath-

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Animal Preparation

Ten healthy dogs were anesthetized with a mixture of ketamine (35 mg/kg), acepromazine (0.75 mg/kg), and atropine (0.5 mg/kg) administered intramuscularly. Pentobarbital (25 mg/kg) was administered intravenously to bring the animals to a surgical plane of anesthesia. Anesthesia was maintained with inhalation of isoflurane (1-2%). A 9F introducer sheath (Meditech/Boston Scientific, Boston, MA) was placed through a right carotid artery cutdown. Heparin (100 IU/kg) was administered. Animals were treated according to the guidelines for laboratory animal care of the National Society for Medical Research, and the Guide for the Care and Use of Laboratory Animals (NIH publication 80-23, revised 1985). The experimental protocol was approved by the Animal Care and Use Committee, and the Institutional Review Board of Johns Hopkins University.

Animal Installation and Scanner Setup

Each of the 10 dogs was anesthetized and placed in the center of a GE 1.5 T CV/i MR scanner (maximum gradient amplitude = 40 mT/m, maximum slew rate = 150 T/m/s). A phased-array surface coil was placed around the thorax. The phased-array coil, MRI guidewire, and MRI-guiding catheter were connected to the scanner on four different receiver channels so that four independent images were reconstructed by the scanner. Simultaneous visualization of the anatomy and the catheters was achieved by merging the four images into one (13). The MRI scanner was operated by a person outside the scanner room. An interventionalist who was located inside the scanner room was able to access the carotid artery introducer during the procedure, since the bore length (160 cm) was relatively short. An in-room monitor was placed in front of the interventionalist to display the images. Images were reconstructed on the scanner, and the real-time data transfer and display programs were run on an advanced development workstation (ADW), a Sun Ultra II workstation (Sun Microsystems, Mountain View, CA), directly connected to the scanner by a high-bandwidth data bus (Bit3 Corporation, St. Paul, MN). The software on this system was modified to enable the real-time images to be superimposed on a previously acquired image (roadmap). The real-time navigation interface was not used in this study. A VCR was used to record the procedures.

Coronary Catheterization

The procedure began with the acquisition of scout images of the aorta and coronary arteries to determine the optimal plan for tracking the guiding catheter. An oblique sagittal slice that would display the arch of the aorta longitudinally, and an oblique coronal slice that would display the ascending aorta and the origin of the left or right coronary artery were acquired (Fig. 2). The parameters were as follows: gated fast spoiled gradient-echo (FSPGR) sequence; bandwidth = 32 KHz; TR = 7.8 ms; TE = 2.5 ms; matrix = 256 × 256; FOV = 32 cm × 32 cm; slice thickness = 4 mm; and imaging time = 19 s. We used one of the two phased-array torso coils wrapped around the chest to obtain the anatomy images.

The MRI-guiding catheter was then introduced into the right carotid artery using the sagittal oblique prescription. We used an FSPGR sequence with parameters as follows: bandwidth = 64 KHz; TR = 4.4 ms; TE = 1.3 ms; flip angle = 7°; rectangular field of view (FOV) = 32 cm × 16 cm; matrix = 256 × 128 (64 phase-encoding steps);

Additional text and figures related to MRI-guided coronary catheterization and PTCA.
Catheterization attempts were performed in the main left coronary artery of each dog, and in the right coronary artery of five dogs. Ten main left coronary arteries and five right coronary arteries were catheterized. Coronary artery catheterization was considered successful if selective 2D projection coronary angiography was obtained. Catheterization times for successful catheterizations were extracted from videotapes from the final five experiments. The first five experiments were not used for time data analysis because recording was incomplete.

Coronary Balloon Angioplasty

In the last two dogs, the MRI guidewire was inserted into the guiding catheter together with a coronary balloon angioplasty catheter (Charger coronary angioplasty balloon (Cordis, Miami); length = 50 cm, catheter internal diameter = 0.36 mm, balloon length = 2 cm, balloon diameter = 2 mm) using the same sequence used for the coronary angiography, but with a 10° flip angle. These catheters were placed successively in the left anterior coronary artery and the circumflex artery. We then inflated the balloon with diluted gadolinium to enhance the balloon on the images using the same sequence that was used for the coronary angiography.

RESULTS

Coronary Catheterization

The interventionalist was able to visualize in real time the MRI-guiding catheter and the surrounding tissues. Using the oblique sagittal orientation, the MRI-guiding catheter was placed into the ascending aorta (Fig. 3a). Using the oblique coronal view, it was then possible to catheterize the left and right coronary arteries (Fig. 3b). The catheterization procedure was successful in all 15 attempts. In the last 10 attempts, the right and left coronary arteries were catheterized in <1 min after introduction of the MRI-guiding catheter into the carotid artery (mean time = 42 s). Four coronary artery catheterizations were obtained in <30 s (Fig. 3c).

The small doses of gadolinium [3 cc, 30–60 mM] administered allowed multiple angiographies to be per-
formed (15), with a spatial resolution of up to 780 μm per pixel (Fig. 4) and no limitation due to intravascular gadolinium accumulation.

Coronary Balloon Angioplasty

The MRI guidewire in the coronary artery was inserted into coronary arteries and tracked on projection images. The entire length of the guidewire in a coronary artery was visible (Fig. 3d).

We were able to place the balloon angioplasty catheter in the left anterior and circumflex coronary arteries of the two dogs. A susceptibility artifact induced by a magnetic ring in the middle of the balloon allowed localization of the balloon catheter on the MRI guidewire (21) (Fig. 3d). Injection of diluted gadolinium in the balloon allowed real-time monitoring of balloon inflation (Fig. 3e).

DISCUSSION

MRI-guided catheterization with active technologies of the coronary arteries requires the availability of multiple techniques and devices, including 1) MRI guidewires and MRI-guiding catheters with specific mechanical properties; 2) high-speed sequences and reconstruction techniques for real-time tracking of MRI guidewires and MRI-guiding catheters, and real-time coronary angiography; 3) multiple receiver channels for simultaneous visualization of instruments and vessel anatomy; and 4) short-bore magnets for accessibility to the patient. Although we show in this study the technical feasibility and availability of all these techniques, there are certain limitations that should be addressed in the future.

A necessary element for successful coronary catheterization is the availability of high-speed sequences. In our study, the use of a fast gradient-echo sequence provided an image acquisition rate of 3.5 frames per second, which was sufficient to catheterize coronary arteries. However, the use of high-speed sequences should increase the quality of the tracking. There are already reports of imaging sequences with a TR of 1.5 ms, which would increase the frame rate by a factor of 3 (22). The use of reduced FOVs for MRI guidewire and MRI-guiding catheters, which would further increase the frame rate by a factor of 32 (23), has also been proposed. Therefore, we believe that the problem of the low frame rate will be solved in a short time. Along with the real-time sequences, real-time reconstruction systems also must improve. In our experiments, we reconstructed 3.5 images per second with four different channels, which is equivalent to real-time reconstruction of 14 images per second (3.5 images per second for each channel). The use of high-speed sequences in the future will require reconstruction systems that can provide simultaneous real-time reconstruction of 15–30 images per second for each channel, which is equivalent to four channels for a reconstruction rate of 60–120 images per second. Such reconstruction systems were not available at the time of our experiments. The delay between the acquisition of an image and its display on the in-room monitor was not a limitation in the execution of the coronary catheterization procedure, because this delay (approximately 100 ms) was small compared to the time needed to acquire each image (280 ms). However, to keep this time to a negligible level with the use of high-speed sequences (50 ms per image), it will be necessary in the future to decrease this delay as much as the acquisition time per image is decreased (from 100 ms to 18 ms if the acquisition time per image is decreased from 280 ms to 50 ms).

As important as the temporal resolution is sufficient spatial resolution for coronary angiography and tracking of the MRI catheters. The method used in this study, which combines intra-arterial injection of gadolinium with the acquisition of a fast gradient-echo projection image, shows high potential for future MRI-guided coronary artery interventions. Similarly to X-ray angiography, this method displays images of the coronary arteries with a spatial resolution of 800 μ per pixel and a frame rate of 3 images per second. However, for this application, both the frame rate and the spatial resolution must be improved. Toward that end, improved phased-array coils and parallel imaging techniques will be helpful (24). Motion artifacts were often seen on coronary angiography images. The spatial resolution of 800 μ per pixel was also insufficient for accurate visualization of arteries that were ≥3 mm in diameter.

Because of the limitation imposed by the frame rate and spatial resolution, we proposed using a sequence that acquires slice-selection images to guide the MRI-guiding catheter selectively in the coronary artery (19). Although this method was very useful in the dogs, and was reliable and easy to use, its use might not be necessary in the future. Furthermore, in humans, specific preshaped guiding catheters for human coronary arteries can be used (which is not possible in dogs). As we have shown in a
preliminary work (13), a projection technique can be used to guide these preshaped guidewires and guiding catheters from a distant vessel to the ascending aorta. If real-time sequences with sufficient spatial resolution become available in the future, such preshaped catheters, combined with a projection imaging technique, may also be sufficient to catheterize selectively coronary arteries. The application of MR guidance and PTCA to humans would then become easy for interventional radiologists and cardiologists already accustomed to the projection imaging technique. Therefore, the slice-selective method we propose should not be considered the only solution for the future, but as a step toward the development of interventional MRI, and as a potential tool to help catheterize coronary arteries of unusual origin.

The use of MRI guidewires in an MR scanner with an electrical connection raises some safety questions. Small currents can be induced in the wires due to applied radiofrequency (RF) magnetic fields. In the present study, plastic-coated nitinol coaxial cables were used with decoupling and balun circuits in order to avoid potential wire heating. Because there was no heating of the MRI guidewire, and no other complications encountered during our experiments, exhaustive safety methods were not used (25–27). In the future, however, complete safety will have to be demonstrated before the technique can be applied to humans. Different solutions have already been proposed for active guidewires, with excellent results (28).

Recently, a coronary stent intervention with the use of passive devices was reported (29). Although the use of such catheters is an exciting area of research for coronary interventions, it presents several limitations. First, the use of passive devices makes positioning of the guiding catheter in the ascending aorta from a femoral access difficult and time-consuming, which is critical in coronary interventions. Second, the guidewire (particularly the portion that is catheterized in a coronary artery) is not visualized along its entire length. Such complete and constant visualization during a procedure is mandatory in order to control advancement and placement in the coronary arteries, especially given their complex 3D anatomy and multiple side branches that are susceptible to perforation. Once the guidewire is in place deep within a coronary artery, such control is also necessary to ensure that the guidewire remains in a stable position and does not pull back during advancement of the balloon angioplasty catheter. Third, the technique presented in Ref. 29 did not involve the use of a guiding catheter, which (to our knowledge) is indispensable for quick balloon angioplasty catheter exchange during a procedure, to provide fast reaction during potential complications. Active techniques, such as described in this study, offer suitable solutions to these problems.

A limitation of MRI-guided interventional techniques is the noise created by the MRI system, which is uncomfortable for patients and makes communication between the interventionalist and the operator difficult. In our experiments, however, successful catheterizations were performed with minimal discomfort. Ear plugs were sufficient to alleviate ear discomfort. The interventionalist and the operator were able to communicate before image acquisition or between two sequences. Already, new MRI systems are being proposed with noise reduction systems. An in-room console to control the sequence and slice orientation from a paddle or a joystick is also being proposed, similar to what is available with X-ray fluoroscopy.

Regarding rapid improvements of the MRI technique, we believe vascular interventions might soon be possible, with potentially significant advantages compared to X-ray fluoroscopy. While they are in the coronary arteries, MRI guidewires can receive signal very close to the surrounding tissues. Atherosclerotic plaque characterization could thus be accomplished, using the capabilities of MRI to differentiate lipids, fibrosis, and calcifications (2–4,29,30). In vivo monitoring of catheter-based vascular gene delivery may be performed (31). MRI also has the potential to provide more comprehensive information about diseased myocardium. The new ability to inject contrast agent selectively in a coronary artery may help physicians evaluate perfusion in a diseased area before an intervention is performed. Finally, interventional MRI could benefit from the ability to navigate on a 2D slice rather than a 2D projection in the heart (32). Intervention that requires direct injection of a therapeutic agent into the myocardium, such as cardiac radiofrequency ablation (33) or injection of VEGF in the myocardium (34), might become possible.

CONCLUSIONS

This study demonstrates the feasibility of MRI-guided coronary artery catheterization and balloon angioplasty inflation in normal coronary arteries. With future improvements in MRI technology and intravascular antenna design, interventional MRI may facilitate treatments for coronary artery and heart disease, and provide new imaging possibilities without the need for ionizing radiation.

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