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Real-time Magnetic Resonance Imaging Guidance for Cardiovascular Procedures

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Abstract

Magnetic resonance imaging (MRI) of the cardiovascular system has proven to be an invaluable diagnostic tool. Given the ability to allow for real-time imaging, MRI guidance of intraoperative procedures can provide superb visualization which can facilitate a variety of interventions and minimize the trauma of the operations as well. In addition to the anatomic detail, MRI can provide intraoperative assessment of organ and device function. Instruments and devices can be marked to enhance visualization and tracking. All of which is an advance over standard x-ray or ultrasonic imaging.

Keywords

real-time; magnetic; resonance; imaging; cardiac procedures

Introduction

The development of Real-time Magnetic Resonance Imaging (rtMRI) allows this imaging modality to provide intraoperative guidance. Traditional computed tomography with contrast can provide excellent spatial resolution but the radiation incurred makes this imaging prohibitive for most intraoperative procedures. Additionally, MRI provides better anatomic detail than fluoroscopic or echocardiographic imaging. Perhaps of equal importance MRI provides a variety of ways to process tissue labeled signal which allows flexibility of slice positioning. rtMRI also provides the ability to change the imaging slice or contrast as is needed

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throughout the procedure. We have previously described the use of MRI guidance for percutaneous interventions including contrast labeled stem cell injection and coarctation stenting (1–5). More recently the use of rtMRI to guide minimally invasive cardiac surgery has been studied (6–8).

rtMRI provides excellent visualization for the surgeon particularly in its ability to provide high resolution images of blood filled structures. It has already become an invaluable diagnostic tool; in addition to the anatomic detail it provides the ability to analyze myocardial function and perfusion (9–10). Recent technologic advances including changeable magnetic field gradients, multi-channel receiver coils, and advanced computing systems have enabled rtMRI to be applicable to the clinical scanner. As a result scanners can provide images up to 30 frames per second without significant latency. Multiple parallel and oblique slices can be obtained in rapid succession and can be simultaneously displayed in a 3D rendering (11–13).

Interactive real-time MRI

One of the strengths of rtMRI is the ability to interactively adjust image acquisition, reconstruction and display parameters during the scan. These interactive features accommodate image contrast, image plane orientations, acquisition speed, 3D rendering and device tracking. Currently some MR scanner manufacturers offer software for adjusting imaging planes and parameters during a real-time scan. Researchers have further developed interactive systems that attach to a clinical MR scanner and provide graphic user interfaces (GUIs) for more sophisticated real-time interactive imaging (14,15).

At the NHLBI we have developed an rtMRI interactive system for use in interventional procedures (16). This consists of an interactive user interface, an operating room large screen display, specialized pulse sequences, and customized image reconstruction software. In this system, a computer with multiple high-performance CPUs and graphics card is connected by gigabit Ethernet to a commercial reconstruction computer of a clinical 1.5-T scanner (Sonata, Avanto or Espree Siemens Medical Systems). With this system, multiple oblique planes can be imaged and displayed simultaneously at their respective 3D locations. High quality images are obtained at approximately five frames per second, depending on imaging parameters, with low latency. The 3D rendering can be rotated on the in-room display to match the orientation of the patient. Image slices can be repositioned, disabled or enabled as needed. The MRI tissue contrast can be interactively channeled by toggling saturation pulses off/on to highlight injected T1-shortening contrast agent. Devices incorporating small receiver coils can be displayed with color-highlight for visual tracking.

Interventional device tracking

A crucial requirement for a MR-guided intervention is reliable tracking of the inserted devices. MRI compatible devices can be visible by incorporating markers, such as “active” coils, or “passive” elements causing signal voids (e.g. steel) or signal enhancement (e.g. gadolinium).

The active markers are small MR receiver coils (16,17). The signal from the coil is bright in the image and can be color highlighted. The receiver coils can be manufactured into different shapes for different purposes. Flexible, long and narrow receiver coils incorporated on a guide-wire or invasive device will allow the entire length of the device to be receptive to MR signal (Figure 1). Small focal coils can be used for tracking individual points (18). Active markers are advantageous since they provide positive image contrast, and if the device exits the imaging plane it may be easily located using projection imaging methods. One limitation of active markers is the potential heating of the coils and the long connecting signal cables.

Passive markers made of paramagnetic materials can be located in the imaging volume using the contrast obtained from the distortion or signal void (19–21). The paramagnetic material typically appears as a dark feature in MR images. The nitinol guide wire, shown in Figure 5, appears as a dark curve in MRI images. Small austenitic stainless steel fragments welded on the side of the stent could show the orientation of the expanded stent as seen in the image (Figure 2). If the imaging field of view is particularly cluttered, such as in vascular areas around the heart, this type of passive marker can be difficult to locate. Another type of passive marker is contrast agent. Catheters filled with Gd-DTPA are evident by bright signal from the lumen (22). The principal advantage of passive markers is the fact that there is no concern about generating unwanted heating.

Real-time MRI guided interventions

The ability of real-time interactive MRI to change imaging and display parameters, tracking the device allows the physician to smoothly perform an interventional procedure. A series of applications are currently being developed with rtMRI guidance (21–29). This section lists a few of these applications that have been investigated at the NHLBI.

Percutaneous transcatheter myocardial injection

In the NHLBI, we have conducted percutaneous transcatheter myocardial injections of gadolinium contrast, and targeted delivery of mesenchymal stem cells labeled with micron-scale iron-oxide particles to myocardial infarct borders (27,28). MR provides visualization of catheter navigation, myocardial function, infarct borders, and labeled cells after injection (Figure 3). With rtMRI guidance the transfemoral guiding catheter traversed the aorta, navigating away from the cephalic vessels and across the aortic valve, using intrinsic blood and tissue contrast. The slices were displayed in 3D. Scan planes were interactively selected to show the aortic arch for LV entry, and rotated along the long axis of the left ventricular catheter for injection site selection. In these experiments, multiple active markers were used. One long MRI receiver coil is built in the transfemoral guiding catheter, and another shorter coil is incorporated in the injection needle. The signals from these coils are highlighted in different colors helped to identify device components.

Percutaneous Stenting of Aortic Coarctation

Another rtMRI guided percutaneous procedure that has been investigated is stenting of aortic coarctation in an animal model (29). Pre-operatively, the margins of the coarctation lesion and the ostium of the subclavian artery were determined with MRI scanning and digitally marked on the 3D-rendered image. The stent-mounted balloon was introduced through the sheath over the active guidewire (Figure 4). The interactive acquisition of multiple planes combined with online 3D rendering provided the physician visualization of the anatomy and the device position. The color highlighting of signal from the active guidewire coils helped track the catheter and guided placement of the stent. The balloon was filled with a small volume of Gd-DTPA to enhance MRI visibility of the device and secure the stent. Stents were deployed at nominal pressure while simultaneously imaging the balloon and aortic wall. Flow and pressure changes after deployment near the stent can be measured to verify resolution of the coarctation immediately post procedure.

Transapical aortic valve replacement

We have investigated the use of rtMRI to provide precise anatomic detail and visual feedback to implant an aortic valve through a minimally invasive transapical approach in an animal model (6,7) (Figure 5). A new short (120cm), wide-bore (70cm) 1.5T imaging system, Magnetom Espree (Siemens Medical Solutions), has been used for MRI guided minimally

invasive cardiac surgery. This magnet design gives a clearance of up to 30cm above the chest of the supine patient, and the short design allows surgical access near the incision. Additionally surgical robot assistance within the magnet becomes quite feasible. The imaging gradients and amplifiers of the new systems yield the same quality and nearly the same scanning performance as that of the standard cardiac MR scanners, and therefore high-quality images can be obtained in real-time with low latency.

For MR guided aortic valve replacement on the beating heart, MR imaging was used to precisely identify the anatomic landmarks of the aortic annulus, coronary artery ostia, and the mitral valve leaflets. Multiple oblique planes were prescribed to delineate the anatomy of the native aortic valve and left ventricular outflow tract. Enhanced by the use of an active marker wire, this imaging allowed correct placement and orientation of the valve to avoid coronary obstruction or impingement on the mitral valve. Via a transapical approach, a series of bioprosthetic aortic valves (21–25mm) were inserted. After the placement of the trocar, the time from implantation to deployment of the valve was less than ninety seconds. In addition to anatomic confirmation of adequate placement of the prosthetic valve in relation to the aortic annulus and the coronary arteries, functional confirmation of the valve and left ventricle was also obtained with MR imaging. Intraoperative perfusion scanning can be used to confirm adequacy of myocardial blood flow after valve placement. Phase contrast imaging can be used to identify intra- or para-valvular leaks. Cine imaging can be used to assess mitral valve function and myocardial function as well.

Conclusion

The traditional imaging methods for guiding intravascular intervention or minimally invasive cardiac surgery, such as x-ray fluoroscopy/angiography and echocardiography, either provide little soft tissue contrast, or are limited by access window and image quality. Compared to these image modalities, MRI provides better image quality and allows procedure planning, device tracking and direct functional assessments prior to, during, and immediately after an intervention. Real-time noninvasive, imaging that can provide both anatomic details and functional assessments will enable minimally invasive beating-heart, cardiac surgery without cardiopulmonary bypass and facilitate other cardiovascular therapies.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

Real-time MR imaging with device incorporating active marker and 3D rendering on a custom reconstruction computer for transapical aortic valve replacement at NIH. Two views of the porcine heart during the insertion of the valve. (a) Shows the valve in a long-axis view (b) shows the valve in a short-axis view. Two blue dots are manually placed markers of the coronary ostia (b). The red signal in both views is the color-highlighted from the marker wire which was sutured to the stent and aligned with a commissure of the prosthetic valve.

Figure 2.

MR Image of passive marker (stainless steel ~0.2mm diameter) on a stent in vitro (a) short axis view and (b) long axis view, and in vivo (c) before and (d) after stent has been expended in valve replacement. The black signal from the passive marker indicates the orientation of the stent inside the beating heart.

Figure 3. MRI guided real-time steady-state free precession image of injection into infarct border. Guided marker channel colored green, needle marker channel colored red, ferritin-labeled mesenchymal stem cells is black.

Figure 4. rtMRI guided percutaneous stenting of aortic coarctation. (a) shows a surgically created aortic coarctation in swine. Stent delivery sequence including (b) advancing balloon/stent over active guide wire and (c) positioning into coarctation and balloon inflation. Courtesy of Robert Lederman.

Figure 5.

Selected frames from real-time MRI displayed within the scan room for transapical valve replacement, showing the deployment of the prosthetic valve. (a) the position of the aortic valve annulus is obvious as the dark line dividing the LV chamber from the aorta. (b) the prosthetic valve is advanced into position in the left ventricular outflow track. (c) interactive saturation is used to enhance visualization of the extent of the balloon (filled with dilute Gd-DTPA) inflation (d) the balloon is deflated and the delivery device is removed from the trocar.