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Magnetic Resonance Imaging–guided Vascular Interventions

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Abstract

Magnetic resonance imaging (MRI), which provides superior soft-tissue imaging and no known harmful effects, has the potential as an alternative modality to guide various medical interventions. This review will focus on MR-guided endovascular interventions and present its current state and future outlook. In the first technical part, enabling technologies such as developments in fast imaging, catheter devices, and visualization techniques are examined. This is followed by a clinical survey that includes proof-of-concept procedures in animals and initial experience in human subjects. In preclinical experiments, MRI has already proven to be valuable. For example, MRI has been used to guide and track targeted cell delivery into or around myocardial infarctions, to guide atrial septal puncture, and to guide the connection of portal and systemic venous circulations. Several investigational MR-guided procedures have already been reported in patients, such as MR-guided cardiac catheterization, invasive imaging of peripheral artery atheromata, selective intraarterial MR angiography, and preliminary angioplasty and stent placement. In addition, MR-assisted transjugular intrahepatic portosystemic shunt procedures in patients have been shown in a novel hybrid double-doughnut x-ray/MRI system. Numerous additional investigational human MR-guided endovascular procedures are now underway in several medical centers around the world. There are also significant hurdles: availability of clinical-grade devices, device-related safety issues, challenges to patient monitoring, and acoustic noise during imaging. The potential of endovascular interventional MRI is great because as a single modality, it combines 3-dimensional anatomic imaging, device localization, hemodynamics, tissue composition, and function.

Keywords

interventional MRI; endovascular procedures; real-time MRI

The trend for the delivery of specific targeted treatment to an organ inside the body over the past 2 decades is very clear: open surgery is out, less invasive procedures are in. Surgical procedures need not be performed just to achieve good access to internal organs. Within the diverse group of minimally invasive interventions, catheter-based interventions are a significant subsection, but doing these under magnetic resonance (MR) guidance is a relatively new and emerging field. Both the absolute numbers and the variety of things that can be done using catheters have been increasing in recent years, in most cases eliminating the need for open surgery. All indicators show that this trend is going to continue into the future.

At present, most catheter-based cardiovascular procedures are guided by x-ray fluoroscopy with or without adjunctive external or intracavitary ultrasound (US). Magnetic resonance imaging (MRI), which provides superior imaging of soft tissue and has no known harmful effects, has the potential as an alternative modality to guide various medical interventions. This article will focus on MR-guided endovascular interventions and give its current state and future outlook.

Magnetic resonance imaging provides anatomic and functional information on the target tissue but at a reduced spatial and temporal resolution compared with radiography. Radiography exposes patients and staff to ionizing radiation. This may be particularly hazardous for children and during procedures requiring extensive radiation exposure,^{1,2} such as, catheter-based ablation therapy for cardiac rhythm disorders. Magnetic resonance imaging has several advantages over US: it does not suffer from acoustic windowing problem, it can image in any arbitrary slice orientation, and exact 3-dimensional position information is known for every MR image.

The potential of MR-guided endovascular procedures has long been recognized, and several excellent reviews of this topic have been published.²⁻¹² The reader is referred to specific reviews for device-related issues or pediatric or neurosurgical applications. Looking at the reviews from the past, one aspect of interventional MRI seems to remain constant over the years: the promises are always much more than what is actually delivered! This general review article of MR-guided vascular interventions will essentially do the same but will focus on recent technical developments and applications. Magnetic resonance-guided prostate interventions, MR-guided neurosurgery, and MR-guided thermal ablation will not be addressed here. First, we will describe enabling technologies, such as developments in pulse sequences and in visualization and postprocessing techniques. Next, we will examine clinical applications, including proof-of-concept procedures in animals and initial experience in human subjects.

ENABLING TECHNOLOGIES

Fast Magnetic Resonance Imaging

Several approaches to achieve faster MR imaging exist. These are listed, in no particular order, and are then examined in detail in subsequent paragraphs:

- Getting a better magnet with stronger and faster gradients
- Getting more signal using balanced gradients (steady-state free precession [SSFP]) during imaging
- Getting more than 1 k-space (frequency-space) lines by refocusing the echo with additional 180° radiofrequency (RF) pulses (eg, fast spin echo)
- Getting more than 1 k-space line within a repetition time (TR) by flipping readout and blipping phase encoding gradients, which is called echo planar imaging
- Using the redundancy of the k-space (eg, asymmetric echo and half-Fourier imaging) or using time interpolation or filtering techniques
- Using alternative k-space trajectories (eg, radial and spiral)
- Using parallel imaging techniques
- Combining ideas above: hybrid schemes

Magnetic resonance-guided endovascular interventions are only possible because of the technical advances in MR hardware and software in the past decade. Better hardware with rapidly switching and stronger magnetic gradients permits faster imaging. A TR of 3 ms will

generate more than 300 distinct echoes per second; if TR is 1 ms, then 1000 echoes could be generated. Additional gains of gradient performance are expected to come with more significant price increases and might be expected to plateau because of limitations in signal-to-noise ratio (SNR) and physiological consequences such as heating or peripheral nerve stimulation. Magnetic resonance imaging is an art of optimization of image parameters for the desired—or, in most cases, acceptable—image quality; interventional imaging usually alters the compromise between temporal and spatial resolution in favor of speed.¹³

During endovascular interventions, the most widely used pulse sequence is balanced gradient imaging technique (also known as SSFP or as balanced fast field echo, TrueFISP, or FIESTA) because of its relatively high SNR in short TR sequences. Steady-state free precession sequences have complex contrast characteristics, but the contrast between different tissues or between tissue and blood can be altered using intermittent magnetization preparation pulses or advanced excitation techniques.¹⁴⁻²¹ Standard gradient-echo techniques can be equally fast (if not faster because there is no need for rephrasing gradients) but usually have an inferior SNR.²² On the other hand, gradient-echo techniques are valuable to enhance and manipulate magnetic susceptibility artifacts. Fast spin-echo techniques are limited because they use rapid 180° RF pulses that increase tissue heat absorption during prolonged imaging. Echoplanar imaging—based techniques have been increasingly used, not in its single-shot image acquisition mode common in brain imaging but as an acceleration factor within the echo time constraints for SSFP sequences.

Alternative k-space sampling trajectories require additional postprocessing to normalize and regrid the data but provide important advantages like small field of view imaging or motion insensitivity. For example, frequency space can be sampled radially so that each echo intersects the center frequency. Spiral or more complex sampling of frequency space can also be used.²³

In echo sharing, echoes are recycled over multiple images and can improve the perceived temporal resolution. For example, using 2:1 echo sharing, a given image updates only half of the frequency space data (using all of the odd lines from the last rectilinear image and using only new data for even lines). This is repeated in an alternating and sliding fashion; hence, imaging speed is effectively doubled (but temporal resolution is not).

Parallel imaging techniques use the fact that receiver coils located at different locations will have different sensitivity maps over the imaged area. Each coil receives the signal from its neighborhood, the final sum being the combined signal coming from all protons modulated by their distances to the coil. This modulation or weighting constitutes the sensitivity profile of that coil. If one has the different combinatorial weighted sums of a signal population, one can compute the original signals via mathematical transformations.^{24,25} Parallel imaging techniques therefore require multiple hardware receiver channel systems, special receiver coils, and increased computational power during image reconstruction. On the other hand, they could readily increase frame rate 2- or 3-fold or more.

Multiple methods can also be combined, for example, incomplete sampling of k-space or sampling of incomplete echoes with echo interpolation or sharing over time. For example, Larson and Simonetti²⁶ combined echo train readout (acquiring 3 echoes at each TR), partial echo readout at odd echoes (using k-space symmetry), and a radial k-space sampling strategy in their fast steady-state projection imaging with dynamic echo-train readout (SPIDER) sequence. Variable and sliding window image reconstructions consisting of few (high temporal resolution) or many (high spatial resolution) echoes can be alternated or used at the same time during continuous MRI. A slightly different approach can be used for multiple field of view imaging in Cartesian imaging.²⁷

Better Computing Power and Visualization Tools

Magnetic resonance images are reconstructed by Fourier-based complex mathematical transformations of original k-space echo data, which can be conducted at a leisurely pace during diagnostic imaging. However, interventional MRI requires immediate reconstruction of images while additional images are constantly acquired. This process requires rapid data transfer capabilities and better computational hardware. The rapid creation of serial images with short latency is called real-time MRI (rtMRI). Although computing power is already available in high-end personal computers for them to be able to handle this type of processes, scanners were not originally specified to operate under such real-time conditions. This resulted in the development of investigational custom software solutions that run on external workstations.²⁸ State-of-the-art MRI systems are now capable of rtMRI at 8 frames per second (fps) or better, with an acquisition-to-display latency of 250 ms or less. On the other hand, in x-ray fluoroscopy, this latency is known to be less than 100 ms. In practice, clinicians seem to find both latency values either acceptable or nearly imperceptible.

Most commercial MRI systems currently provide some interactive real-time image position adjustment functionality during continuous scanning from the MR console. Bidirectional computer communications are used to permit scan control and continuous visualization after image reconstruction. In various research laboratories, there are custom-developed software solutions running in external workstations to improve the speed or ease-of-use of the commercially available systems. These receive either the original echoes or the reconstructed images; display images in 3 dimensions, combined optionally with previously acquired roadmap images; and can perform a variety of postprocessing techniques to enhance images or localize devices. Some of these systems operate in receive-only mode, just to display the images they receive, but most provide additional input to the sequence running at the scanner for changing slice location or contrast characteristics in real time.

Investigational interventional procedures are best guided by multiple slices acquired and displayed in rapid succession. In these multislice acquisitions, a 3-dimensional volume rendering conveying their relative position is extremely useful (Fig. 1). Updates of individual slices can be paused or reactivated to speed the frame rate of other slices. This type of display can also be enhanced by interactive user point-marking to identify the important anatomic features or targets, the ability to make measurements online, and the ability to combine with previous roadmap images to make rapid before-after comparisons.²⁸ An important and desired ability of any interventional MR system is to process signals from individual receiver channels independently, especially those attached to intravascular devices. Operators are able to alter gain settings for each channel interactively. It is also useful for signals from device channels, such as intravascular guide wires or stents, to be displayed in color (Fig. 1). Virtual reality techniques have also been proposed for image display during device manipulation.⁴

Sequence Interactivity

There are 2 general imaging approaches. For some applications, the aim is to direct a device at target pathology while devices are manipulated in or out of the desired target slice. Alternatively, catheter movements can be tracked automatically, and the slice prescription can be updated to keep the desired catheter device always in view while the neighboring anatomy is constantly changing.²⁹ Ideally, both imaging techniques should be available to the operator. During catheter manipulations within target slices, a projection-mode feature becomes very useful. Catheter devices are partially “lost” when parts move outside these selected slices. By toggling the projection mode (which switches to thick-slice imaging), the catheter can be visualized and manipulated back into the target slice. Combining an adaptive projection mode with multislice, 3-dimensional rendering has been also proposed.³⁰

Other useful features include the ability to toggle on and off saturation prepulses to enhance the appearance of gadolinium-based contrast agents during intraarterial injections, to visualize devices such as balloons doped with similar agents, or to visualize hyperenhanced myocardium.³¹ Interactive electrocardiographic gating is also useful to suspend cardiac motion. Image accelerations, such as echo sharing or parallel imaging, should be toggled, and their rate of acceleration should be changed interactively.

Some of the manual sequence interactions above can be automated. For example, Elgort et al.³² reported an interactive sequence that automatically adjusts the field of view and/or temporal resolution depending on the device motion. The pictures are fast but at low spatial resolution during coarse and rapid device movements, and slow but at increased spatial resolution during slow and fine device positioning. Similarly, the field of view may be increased during rapid movement so that one can see the larger anatomic context and decreased to guide fine positioning.³²

Magnetic Resonance Catheter Devices

Things are much more simple and intuitive in x-ray fluoroscopy, where interventional devices are visible because they attenuate x-ray photons. The basic materials that most off-the-shelf devices are made of are intrinsically conspicuous under x-ray. By contrast, in standard MR imaging, structures are visible only when they contain water molecules with excitable proton spins. Catheter devices designed for radiography often contain ferrous materials inside, such as wire braiding, to make them rigid and torque responsive; these ferrous materials distort the local magnetic field and the MR image (Fig. 2). Devices rendered MR compatible by having ferrous materials removed are also rendered invisible because they still do not contain water protons. Moreover, MR-compatible guidewire materials such as nitinol are electrically conductive; when long enough to be clinically useful, they are vulnerable to rapid heating from the MRI RF energy excitation.³³

Passive catheter devices directly influence MR images. Most passive devices appear black using most MRI pulse sequences because they do not contain water protons or cause local susceptibility. Several types of passive tracking markers were tested recently at different field strengths and tracking speeds.³⁴ Guide wires and catheters have been made out of nonmetallic polymers,³⁵⁻³⁷ and early clinical procedures have been conducted using passive CO₂-filled balloon catheters.³⁸⁻⁴⁰ Other examples are gadolinium-filled balloons,⁴¹⁻⁴⁵ gadolinium-filled catheters,^{46,47} and nitinol stents.^{45,48-52} Recently, a multichannel chronic silicon microelectrode system for neural recording and stimulation has been introduced and successfully tested in animal models.⁵³ In comparison with active devices (see next paragraph), these passive devices have reduced technical and regulatory requirements. Therefore, almost all of the clinical experience in humans has been restricted to passive devices so far. Tracking dark devices can be challenging using MRI because a signal void can be could be volume averaged in a larger imaging slice and lots of other things or conditions can cause a signal dropout in MR imaging. In addition, magnetic susceptibility artifacts make the device appear larger than its actual size and can obscure surrounding tissue detail (Fig. 2). Recently, a fully synthetic guide wire that uses a polyetheretherketone polymer core has been proposed.⁵⁴ With small iron particles embedded in its coating, this passive device was tracked using the signal peaks at the side bands of an SSFP sequence with very low flip angles. This is certainly better than tracking signal voids; however, tracking accuracy still needs improvement. Low flip angles are not best for simultaneous regular imaging and might require 2 separate images: 1 for tracking and 1 for the anatomic imaging.

A preferred choice for device visibility is to use modified catheter devices that incorporate MRI receiver coils, or antennae. These active catheter devices are attached to the MRI scanner hardware like any other coil and get signal directly from nearby excited water protons over

their entire length or over a certain profile. These active catheters can be color highlighted in an image overlay.⁵⁵⁻⁶⁰ Early designs were intended for high-resolution tissue imaging or spectroscopy,⁶¹⁻⁶⁷ but there is little enthusiasm to use invasive MRI devices only for diagnostic purposes. The profile of these devices is blurry compared with the sharp profile of devices under x-ray guidance (Fig. 2). The distal tip of these devices is difficult to visualize; therefore, they are not ideal for navigating tortuous or stenotic vasculature. Improved designs have been proposed but not readily available.⁶⁰ Currently, only 1 design, a loopless, active, decoupled and detuned guide wire with a 0.030-in diameter, has regulatory approval in the United States for invasive intravascular MRI procedures in humans.⁶⁸⁻⁷⁰

In another approach, catheters might incorporate small MRI receiver coils that can be tracked with simple localizing pulses alternating with regular imaging within the same pulse sequence.^{66,71-73} Some of these designs also allow high-resolution intravascular MR imaging.⁷⁴ Fast flow velocity measurements using the limited spatial sensitivity of these catheter coils have also been explored.⁷⁵ In pure tracking applications, spatial localization is achieved by a small number of intermittent, nonselective excitations when magnetic gradients are applied in various directions, and a projection echo from the device signal is used to compute the gradient-altered resonant frequency. Several projections are needed to compute the exact microcoil positions in space. The microcoil location is usually depicted as a cross-hair overlaid on the image.⁷⁶ The full length of a device can conceivably be depicted if an adequate number of these microcoils are embedded.

All active catheters described so far require conductive electrical signal-transmitting cable connections to the MRI scanner. These tend to heat if they are longer than 50–80 cm. Several teams have developed circuitry for detuning or decoupling these transmission lines⁷⁷⁻⁸⁰ or have developed alternative transmission lines such as fiberoptics.⁸¹⁻⁸⁴ Several teams have reported wireless active catheters or stents,⁸⁵⁻⁸⁸ which are inductively coupled with the MRI system (Fig. 3). These essentially act as local flip angle enhancers, and device visibility is at its best at very low flip angles. Separating background tissue signal and device signal could be problematic at higher flip angles, but a solution with the use of reverse polarization has been recently proposed (Fig. 4). In a completely different approach, a newly proposed fully optical solution uses the Faraday effect to measure the local magnetic field for device localization.⁸⁹ Heating problems are avoided completely, but both the device size and its localization certainty need to be improved.

GOING INTO THE CLINIC

The main barrier of further clinical translation of this promising field is the limited availability of clinical-grade devices. Nevertheless, a wide range of prototype applications have already been demonstrated in animals, and some early clinical studies have been accomplished. Other clinical studies are currently on their way. The safety aspects of any MR-guided intervention has to be examined in detail, especially if any active or conductive devices will be used during the procedure.⁹⁰

Assembling a Clinical Interventional Magnetic Resonance Imaging Suite

A clinical scanner needs a degree of customization to be suitable for endovascular procedures.⁶⁹ Even in newer, relatively quieter systems, the acoustic noise is sufficiently loud that unassisted verbal communication is not possible and protective headsets are necessary. Commercial solutions are now available using nonmagnetic, sound-suppressing headsets and pneumatic or fiberoptic transmission lines. Their highly directional fiberoptic microphones permit hands-free verbal communications on open channels. An ideal communication system should have a second communications channel, allowing the staff to switch between channels to address each other and/or the patient. Inside the scanner room, good quality video display

is readily accomplished with large-screen backprojection screens or large, shielded LCD displays.

Magnetic resonance–guided endovascular interventions require standard operating procedures that are an extension of those applied for standard noninvasive MRI procedures. All of the required patient care equipment is commercially available for operation in the MRI suite, including patient monitoring equipment, intravenous solution pumps, and mechanical ventilators. One important limitation for cardiac applications is the nondiagnostic quality of electrocardiography because of the magnetohydrodynamic distortion of ST- and T-wave segments; a fast, image-based functional evaluation has yet to prove itself as an alternate method to monitor the heart. As for conventional MRI, interventional staff must be specifically trained, and new MRI interventional procedures must be rehearsed.³⁹

Endovascular Magnetic Resonance Imaging Applications

The size, motion, and contrast characteristics of the target are major determinants for an effective implementation of an MR-guided procedure. It is attractive to target large and thick-walled peripheral arteries, which are relatively immobile, because images can be acquired at acceptable frame rates with relatively high SNR and spatial resolution. Structures that can be imaged within a single plane (such as straight segments of iliac arteries) are more appropriate for MR-guided interventions compared with moving and tortuous structures such as coronary arteries, which are even difficult to image in a non-real-time mode of MRI.

Speuntrup et al⁹¹ demonstrated device navigation and delivery of passively visualized stainless steel stents in the coronary arteries of healthy swine. The devices and proximal coronary arteries were visible using SSFP sequences at 1.5 T. Cardiac and respiratory motion and the small size of coronary arteries especially in diseased states, make this procedure very difficult. Unless there is a major technologic advancement, it is fair to say that coronary artery interventions are not going to be in the forefront for interventional MRI in the near future. Although it gives much more functional information (eg, viability and perfusion) for cardiac myocardial tissue, MR is not near the temporal (15–30 fps) and spatial (200µm) resolution currently enjoyed by x-ray fluoroscopy. This is unfortunate because coronary diseases are one of the most important health problems in the world.

The most common and straightforward MRI-guided vascular applications have been transluminal angioplasty^{42,43,92-96} and stent deployment^{45,48,49,52,97,98} in peripheral arteries. These have been conducted in various animal models. Similarly, investigators have reported placement of vena cava filters⁹⁹⁻¹⁰² and transcatheter visceral embolization.^{103, 104} Other groups have reported rtMRI catheter manipulation using selective arteriography, tracking microcoil-based catheters for selective carotid artery catheterization,¹⁰⁵ passive catheters over active guide wires for selective coronary arteriography,¹⁰⁶ or active catheters for selective visceral artery catheterization.¹⁰⁷ These provided important proofs of concept toward clinical development, and a few human examples of peripheral artery angioplasty and stent deployment have already been reported.^{44,108} These and other human experience in MR-guided interventions will be reviewed at the end of this section.

Critics have asserted that angioplasty and stent deployment do not justify changing imaging modalities to MRI. Certain applications, however, may be particularly well-suited for MRI guidance.

Raval et al⁴⁵ performed MR-guided stenting of aortic coarctation in a pig model. They deliberately used oversized balloons and showed that continuous imaging could reveal catastrophic aortic rupture as it happens. This might offer a potential safety advantage over conventional radiography. In another application, the vessel trajectories in total arterial

occlusion cannot be determined using radiography because the occluded lumen will not fill with contrast to become visible; on the other hand, MRI can visualize vascular spaces even if they are completely occluded. In a pig model of chronic total occlusion of peripheral arteries, Raval et al¹⁰⁹ navigated an active recanalizing guide wire under MR guidance. Magnetic resonance imaging allowed the operators to see and traverse occlusions while remaining within the walls of the vessels.

Aortic aneurysm might present a complex tortuous 3-dimensional structure that could be difficult to visualize using x-ray imaging. Magnetic resonance imaging as a single imaging modality can be used in planning, device deployment, and anatomic and hemodynamic assessment before, during, and after the procedure. In pig models, this was demonstrated first using passive¹¹⁰ and later using custom active devices with endograft stent (Fig. 1).¹¹¹ Treatment under MRI has been shown to restore normal lumen contour and laminar flow in the vessel. More importantly, MRI could demonstrate device apposition and allow interrogation for endoleak.¹¹²

Recently, unmodified, passive stent graft devices have been used under MR guidance in an animal model of thoracic aortic dissection.¹¹³ Magnetic resonance imaging could reveal the true and false lumina of the dissected aorta, guide stent-graft deployment, and immediately demonstrate stent-graft obliteration of the false lumen.

The ventricular myocardium is an attractive target for interventional procedures because its large, thick-walled structure is depicted in high contrast in MRI despite cardiac and respiratory motion. Several cardiac procedures ranging from cardiac catheterization to myocardial injections have been performed under MR guidance and will be examined next.

Schalla et al¹¹⁴ conducted a comprehensive diagnostic cardiac catheterization procedure in a porcine model of atrial septal defect under MR guidance. Using catheters containing tracking microcoils embedded near the tip, they were easily able to accomplish catheterization of the left and right parts of heart, including continuous intracavitary pressure monitoring and blood sampling (Fig. 5). Shunt fractions were then measured using phase-contrast MRI.

Several research groups have used MRI to deliver cells and other materials into specified targets in normal and infarcted animal hearts.^{30,115-119} Multiple slices could be rendered in 3 dimensions to represent their true relationship to each other. Comparable visualization in a beating heart is not available with any other modality, even during open-chest surgery (Fig. 6). When the injectate includes a contrast agent, dispersion of the injected material can be seen directly. This could be valuable for confirming successful delivery, for assuring confluence of treated volumes, and for avoiding overlapping injections. Targeting, in theory, can be based on wall motion, delayed hyperenhancement (infarction), perfusion defects, strain maps, or any other contrast mechanism.

Several groups demonstrated the value of combined tissue and device imaging for the precise placement of prosthetic devices in the heart. A passively visualized nitinol occluder device was positioned to treat porcine models of atrial septal defect, which could be combined with hemodynamics assessment using phase-contrast MRI.¹²⁰⁻¹²² A preliminary experience of deployment of a passively visualized, nitinol-based aortic valve prosthesis has been shown from a transfemoral approach in healthy swine.¹²³ Under x-ray guidance, several catheter-based valve treatments are being field tested already.¹²⁴ Magnetic resonance imaging might be particularly useful in guiding the deployment of such devices in relationship to coronary artery origins and other critical anatomic structures. Atrial septal puncture could provide a direct access to mitral valve for more complex treatments, even replacement, in the future.

Currently, various therapeutic cardiac electrophysiology procedures are conducted using catheter techniques without real image guidance; for example, simple endocardial surface maps are generated using electromagnetic catheter localization techniques during electrophysiological recordings. These rough surfaces might be useful only as roadmaps. They do not account for respiratory and other dynamic changes in cardiac tissues. Therefore, most catheter-based ablation procedures are ultimately guided by multichannel intracardiac electrograms. Surgical exposure often proves more simple and effective, although considerably more morbid for the patient.¹²⁵ Magnetic resonance imaging might provide similar or even better visualization and might enable image-guided transcatheter ablation of cardiac arrhythmia. Magnetic resonance imaging may be particularly useful for visualizing lines of continuity (corresponding to functional electrophysiologic block) after the delivery of ablative energy.¹²⁶ Unlike myocardial injections, the treatment is already known to be effective, and there is a larger group of patients and physicians who could potentially benefit from such procedures.

Initial work on MRI-guided cardiac electrophysiologic procedures is encouraging. Preliminary catheter-tracking experiments using active catheters with specific electronic filters, allowing them to acquire local intracardiac electrograms, have been reported.¹²⁷ Magnetic resonance imaging allows for the characterization of ablated myocardium immediately and over time.¹²⁸ Additional groups have presented animal experiments positioning electrophysiology catheters in an MRI system (Fig. 7).^{76,129,130} Several laboratories are currently working on image-guided therapeutic myocardial ablation in animal models.

Magnetic resonance imaging may enable interventions not restricted to normal lumen spaces. Arepally et al¹³¹ conducted image-guided puncture of the cardiac interatrial septum, a procedure currently conducted primarily using tactile feedback under x-ray guidance. This septal puncture could be followed by balloon septostomy.¹³² Although, similarly, guidance is afforded by intracardiac or transesophageal US, these are important preclinical steps toward more elaborate procedures guided by MRI. Magnetic resonance imaging also allows quantitative assessment of the resulting intracardiac shunts.

Following the theme of going beyond vessel lumen spaces, Kee et al have conducted preclinical⁵⁰ and clinical¹³³ transjugular intrahepatic portosystemic shunt procedures using a unique double-doughnut MRI configuration containing an integrated flat-panel x-ray fluoroscopy system. Magnetic resonance imaging reduced the number of transhepatic needle punctures compared with historical controls. Arepally et al^{134,135} conducted even more difficult preclinical experiments in creating a catheter-based mesocaval shunt outside the liver capsule. These investigators hope to access the splenic and pancreatic venous system using this approach for future biological treatments. This sort of extraanatomic bypass, once made available to nonsurgeons, has the potential to revolutionize mechanical revascularization.

Several groups have already reported investigational MR-guided procedures in patients. Razavi et al³⁹ have conducted diagnostic cardiac catheterization in children using a combined x-ray/MRI (XMR) environment. During MR-guided cardiac catheterization in humans, they examined total pulmonary arterial compliance using MR flow quantification and invasive pressure monitoring.^{136,137} The same group is also conducting x-ray fused with MRI procedures, in which previous MRI datasets are combined with real-time x-ray fluoroscopy to conduct therapeutic procedures.¹³⁸ Kuehne et al⁴⁰ have conducted diagnostic cardiac catheterization procedures using passive catheter devices under rtMRI. Three groups have reported invasive imaging of peripheral artery atheromata using profile-design active guidewire receiver coils.⁶⁸⁻⁷⁰ The used guidewire probably adds little to surface coils for diagnostic MRI of atherosclerosis,¹³⁹ but it might have value in delivering interventional devices. High-quality, selective intraarterial MR angiography^{140,141} and preliminary

revascularization procedures have been reported using passive devices in the iliac and femoral arteries.^{44,51,142} In addition, MR-assisted transjugular intrahepatic portosystemic shunt procedures in patients have been shown in a novel hybrid double-doughnut XMR system.¹³³ Human examples of peripheral artery angioplasty and stenting have been mentioned before,^{44,108} but these used only passive devices. Numerous additional investigational human MR-guided endovascular procedures are now under way in several medical centers around the world.

DISCUSSION

Compared with x-ray imaging, which typically uses 1024×1024 -pixel images at 15 fps, a typical interventional MR image will be 192×128 pixels at 8 fps. The critical question is, “Is the relative information content of these MR images comparable with or better than that of larger-matrix and faster x-ray images?” This has not been fully answered yet.

The potential advantages of endovascular interventional MR are the following:

1. It reduces radiation exposure to patients, especially young patients who are anticipated to require a large cumulative radiation exposure during diagnostic and therapeutic procedures.
2. It reduces radiation exposure to operators and staff, who endure a large cumulative radiation exposure during their careers.
3. It reduces patient exposure to toxic radiocontrast agents, which is important in a minority of patients with kidney disease.
4. It eliminates the requirement that staff wear heavy protective lead garments, which are associated with a high incidence of chronic musculoskeletal injury.

On the other hand, it is stated that endovascular interventional MR represents a costly and cumbersome alternative to procedures that are otherwise conducted rapidly and efficiently under x-ray guidance, and despite any potential benefit, the large capital outlays and expected higher marginal cost of disposable (catheter) equipment are simply unjustifiable. The cost of a state-of-the-art x-ray suite is comparable with that of an MR scanner. Most of the hospitals or imaging centers will need both for regular clinical use. With a little planning during initial installation or upgrade, XMR installations could be a cost-effective solution for interventional MRI. They will also provide adjunctive and bailout treatment environment during the early years of exploratory human research. Moreover, the incremental cost over 2 separate laboratories is fairly low, consisting only of the barrier doors and the intermodality patient transport system. With transitional technologies like x-ray fused with MRI, interventional cardiologists can quickly familiarize themselves with MRI¹³⁸ and might, in time, become more comfortable moving toward full MR procedure guidance in the future.

The potential of MR-guided interventions is great, but there also are significant hurdles: availability of clinical-grade devices, device-related safety issues, challenges to patient monitoring, and acoustic noise during imaging. All are topics of active research and are being addressed by the rapidly growing interventional MRI community. The chief obstacle to the further development of endovascular interventional MRI is the limited availability of clinical-grade catheter devices suitable for MRI. That said, several clinical implementations appear feasible using available technology, and further investigational procedures are underway worldwide.

What would it take for MRI-guided vascular interventions to be the primary image guidance modality for certain procedures? If there is already an established precedence in x-ray with well-known results, then an MR-guided treatment alternative must provide a substantial

advantage over x-ray guidance. Only a much better risk/benefit profile would convince current practitioners to adopt a new method that requires understanding of some new technical expertise and/or reliance on additional team members with such expertise. An alternative strategy would be to focus initially on applications not otherwise possible with radiography and expand the use of MRI in interventions from there.

In time, endovascular interventional MRI could prove itself because as a single modality, it combines 3-dimensional anatomic imaging, device localization, hemodynamics, tissue composition, and function. Magnetic resonance imaging could provide surgical-grade exposure to guide minimally invasive procedures, which have the potential to revolutionize the scope of minimally invasive image-guided treatments.

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FIGURE 1. Demonstration of multislice imaging and color highlighting of active endovascular devices. Three slices are acquired together and displayed in their true 3-dimensional relationship. Shown is an active aortic endograft being positioned using MR guidance in a pig model of abdominal aortic aneurysm. Courtesy of Venkatesh K. Raman.

FIGURE 2.

A comparison of images coming from different catheter designs for MR-guided endovascular interventions. A, Traditional x-ray catheter with a stainless steel braiding causing significant image artifact. B, The same passive catheter without steel braids, rendering it nearly invisible. C, An active catheter that works as an MR signal receiving antenna. Color highlighting of the device channel enhances visualization.

FIGURE 3.

A, Maximum intensity projection of an MR angiogram acquired in the abdominal aorta of a pig after intravenous contrast medium injection gives a comprehensive view of the vascular morphology. B, The active wireless catheter has been guided with real-time projection reconstruction, TrueFISP imaging (1 frame shown), into the celiac trunk. C and D, Maximum intensity projections of selective time-resolved, high-resolution, 3-dimensional, fast low-angle shot contrast-enhanced magnetic resonance angiography (MRA) of the celiac trunk with the superior mesenteric artery in a coronal (C) and in a sagittal (D) projection. Contrast agent was administered through the tip of the wireless active catheter. The distal active end of the catheter is shown in red. Note excellent correlation between the intravenous MRA in panel A and the intraarterial MRA in panels C and D. Courtesy of Harald H. Quick, PhD, University Hospital of Essen, Germany.

FIGURE 4.

A technique for catheter tracking using an inductively coupled RF coil that enables simultaneous acquisition and separation of background and catheter images. In this method, reverse and forward polarization modes of a receive-only birdcage coil, which is connected to the scanner as a 2-channel phased array coil, were used. Magnetic resonance signals acquired from 2 channels were added after phase adjustments to create reverse and forward polarization images. The reverse polarization image contained signal only from the inductively coupled RF coil, whereas the forward polarization image displayed the background. There could be difficulty of precise localization of the catheter if a standard image reconstruction technique is used (A). By using a reverse polarization mode, elimination of the background from the catheter image is possible (B). Color-coded catheter image could be overlaid on the background (C). Courtesy of Haydar Çelik and Ergin Atalar, Bilkent University, Turkey.

FIGURE 5.

Diagnostic cardiovascular catheterization in swine using a tracking-microcoil active catheter. The '+' marker overlaid on the image indicates the tip of the catheter as it advances from the inferior vena cava (A) into the right atrium (B, C) and across the septal defect (D) into the left atrium (E) and left ventricle (F). Hemodynamic tracings and oxyhemoglobin saturation are displayed on the lower panels during pullback. Used with permission from Schalla et al.¹¹⁴

FIGURE 6.

Multislice view of targeted myocardial injection of iron-labeled mesenchymal stromal cells into a small myocardial infarction. This is a rotated view showing both the long axis and short axis of the myocardium. The injection guiding catheter is shown in green, and the needle tip is shown in red. The injected cells appear as a black spot beyond the tip of the needle.

FIGURE 7.

MRI-guided electrophysiologic mapping using active-tracking microcoils. A, MR imaging of this porcine model of healed myocardial infarction reveals the hyperenhanced anterior wall scar (blue arrows), to which an MRI-compatible mapping catheter was manipulated in a real-time fashion. B, A left ventricular substrate map is generated by displaying sinus rhythm electrogram amplitude values onto a 3-dimensional rendering of the chamber. Courtesy of Vivek Y. Reddy, MD, Massachusetts General Hospital.