Interventional cardiovascular magnetic resonance imaging (iCMR) refers to catheter-based therapeutic procedures using MRI rather than conventional radiographic guidance. iCMR promises to further blur the distinction between medical and surgical therapeutics by permitting surgical-quality “exposure” in minimally invasive procedures. Catheter-based procedures conducted without x-rays may be useful in avoiding or reducing radiation exposure to children and clinical staff, in avoiding nephrotoxic radiocontrast, and in reducing staff musculoskeletal injury from x-ray–protective lead aprons. More important, iCMR is exciting because it should permit an entirely new range of procedures otherwise attainable only with open surgical exposure. iCMR requires “real-time” imaging, which for our purposes means image acquisition and display to clinicians, completely refreshed 1 to 10 frames per second, depending on the application, within a short delay (approximately 250 ms).

Clinical investigational procedures have begun at several centers. The chief limitation to clinical translation, at present, appears to be the availability of clinical-grade catheter devices. This brief review will survey interventional cardiovascular magnetic resonance imaging, treatment, and patient handling considerations; unique iCMR catheter design requirements; proof-of-concept animal and clinical experiments conducted to date; and novel applications we can expect in the near future.

How MRI Creates Images for Intervention

MRI is possible because water protons, ubiquitous in tissue and blood, have magnetic moments (or “spins”) that align in a magnetic field like compass needles. These spins have a characteristic resonance frequency at which they absorb electromagnetic radiation, a frequency that varies with the intensity of the surrounding magnetic field. Exposed to radio waves, spins become energized at these characteristic frequencies and afterward emit radio signals (“relax”), a process that can be detected with sensitive radio hardware. Pictures of tissues inside the magnet bore are created by “encoding” the position of proton spins in space by using small magnetic field changes (gradients). The positions correspond to known emitted frequencies, either while the spins are being energized or while they are discharging radiofrequency (RF) energy. The emitted signal contains a mixture of frequencies that can be mathematically decoded into an image. The timing of the RF pulses and magnetic field gradients in appropriate MRI “pulse sequences” determines image contrast. The biochemical and physical properties of body tissues permit a wealth of possible MR image contrasts based on tissue composition, distribution, and motion—not merely on atomic density as in x-ray.

iCMR is now possible because technical advances permit rapid imaging on clinical scanners. These include highly uniform magnetic fields, rapidly changeable magnetic field gradients, multichannel receivers, and advanced computing systems. Newer systems have permitted clinical implementation of rapid and efficient pulse sequences such as steady-state free precession (SSFP; also known commercially as TrueFISP, FIESTA, or Balanced FFE) that provide excellent contrast between blood and myocardium. Imaging speed is limited by the physiological limits of stimulating patients’ peripheral nerves (from rapidly changing magnetic fields) and of heating (from prolonged RF excitation). These problems are more pronounced at higher field strengths. Faster pictures come at the expense of reduced spatial resolution. For comparison, x-ray–guided interventions are currently performed using 512×512- or 1024×1024-pixel matrices; most rtMRI interventional procedures use 256×192 or smaller pixel matrices. However, the information content of these images is comparable to or higher than x-ray because of tissue and blood visualization (Figure 1).

Configuring a Suite for Clinical Interventional MRI

Investigational iCMR may require adjunctive or emergency bailout x-ray fluoroscopy (XRF); the two are combined into so-called XMR suites. For example, the NHLBI intervention suite consists of independently operating MRI and XRF systems (Sonata 1.5T and Axiom Artis FC, Siemens, Figure 2) separated by RF-shielded sliding doors. A motorized transport system (Miyabi, Siemens) permits rapid, smooth...
intermodality patient transport. In-lab image display can employ either shielded LCD screens or projectors. To attenuate acoustic noise and permit open-microphone communication among the operator, staff and patient, we use directional optical microphones (Phone-Or) attached to RF-filtered headsets (Magnacoustics) using two communications channels. Modifications to the way magnetic gradients are changed and newer, quieter MR systems may ameliorate the acoustic noise problem.

iCMR poses new challenges to patient handling, monitoring, and safety. We use custom multiple-lead RF-shielded ECG cables (In Vivo Research) because the rapidly switching magnetic gradients and RF pulses used to create images can heat standard cables, causing skin burns, or can induce signal artifacts resembling arrhythmias. Moreover, cardiac and aortic blood flow within the main magnetic field irreversibly distorts ECG ST segments, so at present ECG is nondiagnostic and is used only for identifying heart rate and periodicity. Other systems use vectorcardiographic signals to optimize cardiac rhythm detection to gate image acquisition and to monitor patients. Inside the interventional suite, all ferromagnetic equipment (ie, infusion pumps, ventilator) should be substituted with MRI-compatible equipment. A pathway must be available to evacuate the patient rapidly from the high magnetic field during emergencies. For example, discharging cardiac defibrillation paddles within the high magnetic field can easily knock down emergency caregivers, and the defibrillator or other resuscitation equipment moved in proximity to the MRI bore can become missiles.

Sedated or otherwise noncommunicative patients (ie, during general anesthesia) also need to be protected from heating during prolonged rapid MRI examinations, either by monitoring predicted specific absorption rate (SAR) during RF excitation or by actual temperature monitoring. Perhaps the most important safety consideration is careful training of all personnel who might enter the suite.

All contemporary MRI scanner systems offer basic real-time mode, with online interactive slice prescription during scanning. Meaningful therapeutic procedures may require more advanced functionality, including real-time multislice acquisition and 3D display and color highlighting of catheter channels. These features are available or under development by most hardware vendors.

In addition to anatomic images, investigational systems can provide additional functional information to guide procedures, such as real-time (“Doppler-like”) flow mapping.

Intravascular Devices

Most contemporary XRF catheter devices employ ferrous braiding to improve catheter stiffness and torque responsiveness. Ferrous materials degrade MR images unacceptably. Substitution with nonferrous materials usually renders the devices poorly visible under MRI and often degrades mechanical performance. A number of approaches to this problem are depicted in Figure 3 and reviewed briefly below.
Passive Catheter Designs

“Passive” catheters, visualized based on intrinsic materials properties, are attractive in their simplicity and safety but overall are not sufficiently visible.

Polymer catheters or guidewires with embedded metals can be tracked on the basis of signal voids (dark spots) induced by magnetic susceptibility artifacts.

Real-world navigation of passive catheters is challenging. Volume-averaging refers to detail lost when image voxels are larger than small volumes of interest. The dark spots created by passive catheters can be obscured by volume-averaging and therefore require imaging slices too thin to work with. Moreover, catheter elements can be “lost” when they move out of the selected imaging slice, and the “bloomed” signal voids caused by embedded metals can obscure nearby tissues. Nevertheless, clinical catheterization has successfully been conducted by tracking signal voids, such as those induced by CO₂-filled balloon catheters.

Investigators have successfully navigated passive catheters in vivo that are brightened because they are filled with gadolinium contrast. A shortcoming of this approach is that the lumen is no longer available to deliver other devices or agents. There has been little in vivo success coating catheters with gadolinium-like agents.

Active Catheter Designs

“Active” catheters incorporate MRI receiver coils for imaging, tracking, or both. In early designs, catheter coils were placed directly against tissue to produce high-resolution imaging or spectroscopy.

Some active designs induce electronically controlled magnetic field inhomogeneities that cause signal voids, visible in part because they can be turned on and off. These suffer similar limitations to passive designs because they use signal voids to indicate their position.

Active catheters that contain MR receiver coils are more conspicuous as they move within the body. Typically these designs make the entire length of catheters visible (Figure 3C). An added benefit of these designs is that catheters can be visualized even if they move outside the selected imaging slice (Figure 4). Some approaches use the catheter coil both for signal detection and for RF excitation. Alternatively, active catheters with focal coils have been used to track individual points on the catheter. This requires minor modifications of the pulse sequences used to acquire the images (ie, a small number of nonselective excitations intermittently to locate the markers in space). Cross-hairs indicating coil position can be overlaid on top of road-map or image frames as they are updated (Figure 3E). Position or motion of such tracking coils can be used automatically to specify MRI parameters such as scan plane or field of view. Similarly, surgical (and soon catheter) devices are commercially available incorporating multiple orthogonal magnetometers that, used in conjunction with known gradient sequences, can be used to determine catheter position. Such active tracking coils and magnetometers are attractive in their simplicity but insufficient to visualize the entire length of catheters, a feature that may be important for navigation or to recognize, for example, catheter devices that kink or otherwise fail. One possible solution would be to embed multiple tracking coils along the length of the catheters.

By virtue of incorporating long conductive elements, active catheter designs risk heating during the RF excitation required for MRI. Several investigators have addressed this problem by incorporating circuitry for detuning or decoupling the conductive wire during RF excitation, thereby preventing heating. Some promising recent decoupling approaches incorporate transformers into the transmission.
Hybrid and Multispectral Catheter Designs

Hybrid designs have been demonstrated that incorporate tuned receiver coil elements—but not connecting wires—into catheters\(^{60,61}\) or even stents.\(^{62,63}\) These inductively coupled designs can provide much of the visibility of traditional active devices without the potential heating problem of conductive transmission lines (Figure 3F).

Multispectral MRI, visualizing spins from species other than water protons, is an exciting new concept being explored for passive catheter tracking by several groups. Kozerke et al.\(^{56,57}\) have demonstrated MRI tracking of \(^{19}\)F-filled catheters in phantoms. Golman’s team has demonstrated in vivo catheter tracking and angiography using hyperpolarized \(^{13}\)C-hydrocarbons.\(^{65,66}\) Concurrent or interleaved proton and non-proton MRI might combine the superior tracking ability of active devices with the safety of passive devices.

Applications

A compelling array of applications has been reported for interventional cardiovascular MRI in animal models.

Cardiac

Schalla et al have demonstrated transvenous and transarterial cardiac catheterization in a porcine model of atrial septal defect wholly using iCMR and tracking receiver microcoils to mark catheter tips.\(^{67}\) They navigated catheters among cardiac chambers to obtain invasive pressure and oximetric measurements. The strength of this demonstration is its excellent simulation of clinical procedures; the weakness is the inability to visualize the length of their catheters, an important safety limitation in clinical procedures. Voiz et al.\(^{68}\) have recently demonstrated local flow assessment using intravascular receiver coils, and Thompson et al.\(^{69}\) assessed flow noninvasively using complex-difference phase contrast, both of which might prove useful adjuncts during cardiovascular catheterization.

Our group has conducted percutaneous transcatheter myocardial injection of gadolinium contrast,\(^{70}\) and in a later iteration, targeted delivery of iron-labeled mesenchymal stromal cells to myocardial infarct border targets.\(^{71}\) These used multiple active intravascular devices, visible along their entire length, combined with rapid sequential imaging of multiple slices. The slices were displayed in 3D and used colors to highlight catheter-related signal (Figure 1B and Figure 4). The strength of the demonstration is the simulation of clinical procedures, with excellent target and catheter visualization, and instantaneous rather than roadmap myocardial targeting, such as that provided by electromagnetic positioning (eg, Biosense NOGA). The weaknesses are that the utility of precise cell delivery remains unproven and that catheters are not available for clinical testing. Other groups also have used retrograde transaortic access to conduct image-guided myocardial injections.\(^{71–74,74a}\)

Kuehne et al.\(^{75}\) demonstrated MRI-guided transcatheter aortic valve replacement in swine using passive nitinol devices. This application is attractive because of the critical importance of image-guided placement of the stent-valve in relation to the coronary arteries and aortic root. However, such susceptibility-based device imaging alone probably will not be satisfactory in this application.

Three groups\(^{76–78}\) have deployed passive nitinol atrial septal defect (ASD) occluders in porcine models. Although these are good demonstrations, it remains unclear whether iCMR adds clinical value in positioning ASD occluders compared with XRF and concurrent intravascular or transesophageal ultrasound guidance.

Cardiac electrophysiologists ablate myocardium to alter local myocardial conduction and interrupt symptomatic atrial or ventricular arrhythmias. Currently these are guided functionally using electrograms and electromagnetic mapping, with adjunctive image guidance using XRF or ultrasound. Primarily image-guided myocardial ablation is an interesting alternative that currently is conducted under direct surgical guidance\(^{79}\) and that might be conducted under iCMR. Preliminary catheter tracking with acquisition of filtered local electrograms has been reported,\(^{80}\) as has MRI characterization of ablated myocardium.\(^{81}\) The Massachusetts General Hospital team has conducted real-time MRI positioning of an electrophysiological catheter overlaid onto high-resolution time-resolved (4-dimensional) images of infarcted pig myocardium\(^{82}\) (Figure 5).
Several groups have reported percutaneous coronary artery intervention in healthy animals, some showing spectacular images of intracoronary stent artifacts. These works, though impressive, may not readily be translated into clinic. Using contemporary proton MRI, it is not clear that iCMR-guided coronary intervention ever will be feasible. Traversing complex coronary lesions require delicate guidewire and device manipulation, and currently this is conducted under XRF guidance with device imaging at 200-μm spatial resolution in a 512–1024 square pixel matrix at 15 to 60 frames/second. Comparable spatial or temporal resolution does not appear accessible with available MRI technology.

A promising recent development is the report of successful iCMR-guided atrial septal puncture by Arepally et al. Our labs also have successfully employed this procedure to enable balloon atrial septostomy (Figure 6). These iCMR demonstrations are noteworthy because they show cardiovascular procedures need no longer be confined to vascular chambers and lumens. In particular, this technology likely will soon enable extra-anatomic bypass procedures such as palliative left-right extracardiac shunt or aortofemoral bypass, procedures that at present require open surgical exposure. Even catheter-based valve repair procedures may prove feasible.

**Extra-Cardiac**

Several groups have conducted angioplasty and stenting using passive and active catheter techniques in animal models of arterial stenosis. Similarly, groups have positioned aortic aneurysm endografts, inferior vena cava filter devices, and have embolized renal artery segments using iCMR. These are important proofs of concept toward clinical application, but such demonstrations in healthy animals or simple disease models are relatively limited: For the most part, they require simple axial displacement of devices compared with difficult device navigation and positioning in patients with complex atherosclerotic disease.

Perhaps more exciting are recent novel procedures that demonstrate the real strength of iCMR to provide surgical-grade exposure for minimally invasive procedures that are not adequately guided by XRF or that require open surgery. Our group has recanalized long segments of chronic total arterial occlusions in an animal model. Using custom catheter and guidewire coils, we were able to traverse long segments of occlusion while keeping within arterial adventitial borders, an important clinical challenge (Figure 7D–7E). Arepally et al have made a transcatheter mesocaval shunt, or extrahepatic connection between portal and systemic venous circulations, first using a septostomy needle and then deploying a novel custom vascular connector (Figure 8). A team at...
Stanford integrated a flat-panel XRF system into a double-doughnut operative MRI system and conducted dual-modality transjugular intrahepatic portosystemic shunting (TIPS) in animals\textsuperscript{105} and in patients\textsuperscript{106} and showed a reduction in number of punctures required compared with historical controls.

**Early Human Experiments**

A few human iCMR procedures have been conducted. Razavi et al\textsuperscript{20} reported a landmark series of cardiac catheterizations in children using a combined XMR environment. The same group is conducting x-ray fused with MRI (XFM) procedures, in which prior MRI datasets are combined with real-time XRF to conduct therapeutic procedures (Figure 9). The Hopkins team\textsuperscript{59} and others\textsuperscript{9,59a} have reported invasive receive coil imaging of human peripheral artery atheromata. The Regensburg team has conducted high-quality selective intra-arterial MR angiography\textsuperscript{107} and has reported some preliminary revascularization procedures using passive devices in the iliac\textsuperscript{108} and femoral\textsuperscript{109} arteries. As described above, the Stanford team has conducted iCMR-assisted TIPS procedures in patients.\textsuperscript{106}

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**Figure 7.** iCMR left ventricular electroanatomic mapping in a pig model of chronic myocardial infarction. Real-time in vivo catheter tracking using active MR tracking coils on a deflectable electrophysiology catheter introduced across the interatrial septum and mitral valve into the left ventricle. Left ventricular substrate maps combined contact-catheter–derived electrical activity (bipolar voltage amplitude) onto the MRI-derived 3D model of the endocardial shell. A, Anterograde myocardial infarction is detected by reduced voltage. B, Instantaneous location of the MRI-compatible catheter is mapped using the active tracking coils (short blue segments); both the distal shaft of the catheter (the connecting yellow spline) and the extrapolated catheter tip (red sphere) are shown within a wire mesh constructs of the volume rendering of the left ventricular cavity. Courtesy of Vivek Y. Reddy, MD, and Godtfred Holmvang, MD, Massachusetts General Hospital; Ehud J. Schmidt, PhD, and Charles L. Dumoulin, PhD, GE Global Research, Inc.

**Figure 8.** MRI-guided transcatheter meso-caval connection using a novel nitinol connector (top). Bottom left: MRI puncture needle directs guidewire from inferior vena cava into portal vein. Bottom middle: Intraperitoneal MRI balloon angioplasty. Bottom right: XRF confirmatory angiogram of successful mesocaval shunt. Courtesy of Aravind Arepally, Johns Hopkins University.

**Figure 9.** A human XFM procedure. A, 3D volume rendering from baseline MRA before stent implantation. B, XFM-guided stent implantation, combining phase-contrast MRI with real-time XRF depicting a long sheath in situ and the stent within the aorta in the target coarctation (courtesy of Reza S. Razavi and Sanjeet Hegde, King’s College London).
Future Prospects and Conclusion
Clinical cardiovascular interventional MRI appears feasible and is entering clinical testing using currently available technology. Progress in clinical development has been impeded by several factors. Many research and clinical institutions are concerned about the large capital outlay required to install XMR suites. Standard, independently operable, combined clinical XRF and MRI suites are readily configured for iCMR; the only incremental capital outlay required is for the intermodality transport table and for shielded RF doors separating the systems. The limited deployment of iCMR and XMR suites has created a reciprocal problem in which industry has shown little interest to develop interventional MRI catheter devices, which in turn inhibits wider translation of the technology. Competing technology is under development, particularly for minimally invasive procedures combining images from multiple real-time and retrospective imaging modalities including XRF, 2D and 3D-ultrasound, MRI, CT, and electromagnetic positioning.

However, iCMR offers single-modality solutions that may prove superior. In particular, iCMR may enable a range of breakthrough applications, such as image-guided ablation to treat cardiac rhythm disorders, minimally invasive extra-anatomic bypass, and beating-heart valve repair. Not only can iCMR provide surgical-grade exposure for clinicians, it can visualize the immediate effects of treatment upon target tissue. Overall, iCMR guidance for transcatheter cardiovascular procedures has the potential to revolutionize the way interventionalists operate, enabling minimally invasive procedures otherwise impossible with conventional imaging guidance.

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