Interventional Cardiac Magnetic Resonance Imaging in Electrophysiology

Advances Toward Clinical Translation

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Technical advances in cardiovascular electrophysiology have resulted in an increasing number of catheter ablation procedures reaching 200,000 in Europe for the year 2013.1 These advanced interventions are often complex and time-consuming and may cause significant radiation exposure.2 Furthermore, a substantial number of ablation procedures remain associated with poor (initial) outcomes and frequently require ≥1 redo procedures.3

Innovations in cardiac imaging and image guidance could help improve the results of ablation procedures.4 Among the available imaging modalities, Cardiac MRI (CMR) can be considered the most comprehensive and suitable modality for the complete electrophysiology and catheter ablation process (including patient selection, procedural guidance, and [procedural] follow-up).5 The unique ability of CMR including tissue characterization (eg, T2-weighted imaging for edema visualization, late gadolinium enhancement [for necrosis quantification]) may be of advantage for the evaluation of lesion formation and therapeutic efficacy.6,7 These benefits and the lack of radiation exposure inspired the development of hybrid x-ray/MR (XMR) suites10 and dedicated interventional CMR (iCMR) units.11

This review examines the requirements and clinical feasibility of a dedicated iCMR suite for electrophysiology procedures. First, the limitations of current electrophysiology procedures and ablation strategies are analyzed and the advantages of an iCMR suite for this purpose are discussed. Second, the clinical feasibility is examined by presenting the current challenges of working in an MRI environment. Safety, imaging, and device-related aspects are also reviewed. Finally, the requirements for implementing an iCMR suite and the current state of their developments are addressed.

Current Challenges in Electrophysiology

There are different phases during the workup and follow-up of a diagnostic or ablative electrophysiology procedure. The limitation of the current strategy, including the role of fluoroscopy, in diagnosis and treatment of arrhythmias is discussed in the following paragraphs.

Patient Identification and Procedure Planning

Imaging is considered a cornerstone of patient selection for ablation therapy.4 Information about arrhythmic substrate can be acquired before the procedure using CMR. However, despite the proven usefulness,12,13 preprocedurally acquired data are usually not merged with the electric anatomic mapping (EAM) systems. The integration of preprocedurally (noninvasively) acquired data (ie, MRI-based anatomic and pre-existing scar road map) may result in shorter durations of the invasive, X-ray-based conventional procedures. The use of iCMR would allow these advantages although reduced procedure times might not be seen initially because of the learning curve of doing the procedures in a new environment.

Procedural Radiation

The use of electroanatomic mapping systems has led to some reduction in radiation exposure form the historically high doses seen in electrophysiology procedures. There are in addition several new developments that focus on further reduction of radiation exposure. A recent example is the MediGuide (St. Jude Medical Inc, St. Paul, MN) system, a novel 4-dimensional (4D) electromagnetic catheter tracking technology. It allows visualization of catheters inside angiographically derived left atrium models and prerecorded cine-loops. The system is aimed to reduce radiation exposure by limiting fluoroscopy duration. Although studies illustrate that electrophysiology procedures significantly benefit from this technology,14,15 it still awaits widespread clinical implementation. However, iCMR would completely eliminate radiation exposure even in long complex cases.

Therapeutic Efficacy

Particular ablation procedures such as atrial fibrillation and ventricular tachycardia ablations are often associated with ≥1
redo procedures. Recent studies, based on MRI techniques including T2 and late gadolinium enhancement, have proposed an explanation for this phenomenon.9,12 During radiofrequency ablation there is formation of edema and necrosis.9,16 After ablation, edema gradually disappears and gaps between adjacent ablation lesions become apparent. These gaps or areas with incomplete isolation result in recurrence of arrhythmia. Identification of gaps in advance may facilitate redo procedures substantially (Figure 1).12 However, this requires a robust imaging strategy for gap identification. Furthermore, the integration of the generated gap information needs to be easily integrated into the EAM system. Current EAM systems unfortunately do not offer this functionality.

It is safe to conclude that despite various technological advances, there is substantial need for further improvements in the current electrophysiology and ablation treatment and evaluation strategy. To a large extent, these developments (eg, improved procedural guidance, reduction of radiation exposure, and evaluation of procedural efficacy) could theoretically be achieved by operating in an iCMR environment.

iCMR in Electrophysiology

iCMR allows for integrated use of preprocedural 3-dimensional (3D) anatomic scans to help guidance of active tracked catheters, periprocedural interactive multiplanar visualization of relevant anatomy and visualization of the extent of ablation lesion, as well as evaluation of complications. The therapeutic strategy incorporating these information could potentially improve the electrophysiology procedure by reducing procedural time and increasing (therapeutic) efficacy, including less redo procedures.

A limited number of centers have explored the (clinical) possibilities toward performing electrophysiology procedures (diagnostic and ablation) in an MRI environment (the vast majority at 1.5 Tesla [T]; Table 1). The majority of these studies have been performed in animals. To date, the limited number of (safety) studies conducted in humans has been successful and uncomplicated. However, each research group concludes that before performing iCMR-guided ablation procedures on a routine basis, the following challenges need to be overcome: (1) equipment (eg, communication headsets, catheters and mapping systems) needs to be modified to ensure MR compatibility and allow active tracking possibilities, (2) image acquisition protocols and reconstruction frameworks need to be standardized, and (3) existing operational and safety workflow requires considerable modification.

### Equipment

**Device Tracking**

There are 2 approaches to track devices in an MRI environment: passive and active. Both techniques have their unique advantages and shortcomings.

**Passive**

Passive tracking uses the signal void and susceptibility artifact caused by the device because of local inhomogeneity of the magnetic field.32 The passive approach requires continuous tracking of the artifact during in-plane device movement. This requires ongoing adjustments to the imaging plane by the operator. This is a difficult and time-consuming task that requires skilled operators. Furthermore, incorrect imaging plane selection during in-plane manipulation can result in loss of device visualization and may increase procedural duration. In addition, loss of anatomic information might occur in the area surrounding the artifact, reducing differentiation between various tissues and may hamper precise navigation.

Despite these disadvantages, both diagnostic electrophysiology procedures and ablations have been performed successfully in patients using passive tracking (Figure 2A).27,31

**Active**

Active tracking is performed using small radiofrequency receiver coils built into the device. Imaging sequences can interrogate the location of these coils and allow for real-time, device-only navigation.33 The current electrophysiology procedures often require multiple different (multielectrode) catheters. To get accurate orientation of a catheter and be able to use predetermined models of the shape of the distal end of the catheter where the electrodes are placed, ≥2 active coils are needed. These coils have a hypothetical danger of heating because of radio-frequency coupling.34 However, there have been several strategies developed to address this.35 However, because of this safety concern, active tracking has to date

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**Figure 1.** Isolation gaps detected using late gadolinium enhancement (LGE) and used for redo ablation guidance. **Left.** The first pulmonary vein isolation electric anatomic mapping (EAM). Certain gaps are visible between the radio-frequency application points (red dots). **Center.** The scarmap generated using LGE images acquired 3 months after the procedure. Tissue characteristics are color coded, blue is healthy myocardium, whereas red defines scar/fibrosis. The black circle demonstrates a good visual correlation between the extent of ablation on the EAM and presence of scar on the LGE. Two major gaps are visible on the scarmap (dashed black circle). During the redo procedure (right) these gaps were targeted (dashed black arrow). LIPV indicates left superior pulmonary vein; LSPV, left inferior pulmonary vein; RIPV, right inferior pulmonary vein; and RSPV, right superior pulmonary vein.
only been studied in animal models (Figure 2B).\textsuperscript{11,23,24,29} Initial reports did not encounter any adverse events.

**Devices**
The availability of MR-compatible devices is currently extremely limited. The majority of the devices are used for investigative purposes and are yet to obtain regulatory approval.

**Instrumentation Electrophysiology Study**
A conventional electrophysiology study requires a recording and mapping system, stimulator, and an radio-frequency generator. Currently, there is no MRI-compatible equipment available commercially. As a result, every center has their own customized solution. Several centers are investigating devices from Imricor Medical Systems (Burnsville, MN) and MRI Interventions (Irvine, CA). These companies are in the process of developing a range of MRI-compatible devices with regulatory approval.\textsuperscript{24,25,31}

**Electric Anatomic Mapping**
An important component of the conventional electrophysiology studies are the EAM systems that allow for catheter navigation inside realistic anatomic heart models. Recent studies have proposed modifications to create MRI-compatible EAM systems.\textsuperscript{36} The introduction of such an EAM system will offer the prospect of a fully integrated approach, suitable for MRI-based navigation, deployment of specific, targeted ablation, and immediate evaluation of therapy.

**Catheters**
An essential component in performing electrophysiology procedures are the diagnostic and ablation catheters. Both passive and active catheters have been used for investigational purposes in animals. However, because of safety concerns (heating) all human trials have been conducted using passive tracking only (Table 1). Although active tracking is not a prerequisite for iCMR-guided electrophysiology, active catheters can be used for device-guided navigation. This feature eliminates operator interaction for manual scanning plane adjustment. In addition, the improved visibility of active catheters may contribute toward reducing procedural duration.

**Guidewire**
Performing interventional electrophysiology procedures may require the use of guidewires to facilitate the insertion of multiple sheaths and guidance of some catheters required during ablation. Passive guidewires have been applied successfully during cardiac interventions and are being investigated in larger trials.\textsuperscript{37} The major limitation of using active guidewires is the potential of radio-frequency coupling because of the substantial length of these devices. This restriction has been addressed recently by the development of an active guidewire with embedded fiberoptic temperature probe.\textsuperscript{38} Although this new feature does not eliminate the risk of heating, the temperature probe allows accurate monitoring of device heating and contributes toward safer usage of guidewires.

### Table 1. Real-Time MRI-Guided Electrophysiology Studies

<table>
<thead>
<tr>
<th>Year</th>
<th>Reference</th>
<th>Population</th>
<th>Procedure</th>
<th>Magnet (T)</th>
<th>Catheter Tracking</th>
</tr>
</thead>
<tbody>
<tr>
<td>2008</td>
<td>Nazarian et al\textsuperscript{11}</td>
<td>10 dogs/2 humans</td>
<td>Diagnostic study</td>
<td>1.5</td>
<td>Passive and active</td>
</tr>
<tr>
<td>2008</td>
<td>Dukkipati et al\textsuperscript{27}</td>
<td>14 swine</td>
<td>Diagnostic study</td>
<td>1.5</td>
<td>Active</td>
</tr>
<tr>
<td>2009</td>
<td>Schmidt et al\textsuperscript{28}</td>
<td>8 pigs</td>
<td>Diagnostic and ablation study</td>
<td>1.5</td>
<td>Active</td>
</tr>
<tr>
<td>2009</td>
<td>Nordbeck et al\textsuperscript{19}</td>
<td>8 pigs</td>
<td>Diagnostic and ablation study</td>
<td>1.5</td>
<td>Passive</td>
</tr>
<tr>
<td>2010</td>
<td>Hoffmann et al\textsuperscript{20}</td>
<td>20 pigs</td>
<td>Diagnostic and ablation study</td>
<td>1.5</td>
<td>Passive</td>
</tr>
<tr>
<td>2011</td>
<td>Nordbeck et al\textsuperscript{21}</td>
<td>9 mini pigs</td>
<td>Ablation study</td>
<td>1.5</td>
<td>Passive</td>
</tr>
<tr>
<td>2012</td>
<td>Eitel et al\textsuperscript{27}</td>
<td>1 human</td>
<td>Diagnostic study</td>
<td>1.5</td>
<td>Passive</td>
</tr>
<tr>
<td>2011</td>
<td>Vergara et al\textsuperscript{23}</td>
<td>6 pigs</td>
<td>Diagnostic and ablation study</td>
<td>3.0</td>
<td>Active</td>
</tr>
<tr>
<td>2012</td>
<td>Ranjan et al\textsuperscript{24}</td>
<td>12 swine</td>
<td>Diagnostic and ablation study</td>
<td>3.0</td>
<td>Active</td>
</tr>
<tr>
<td>2012</td>
<td>Ganesan et al\textsuperscript{25}</td>
<td>12 sheep</td>
<td>Diagnostic and ablation study</td>
<td>1.5</td>
<td>Passive</td>
</tr>
<tr>
<td>2012</td>
<td>Nordbeck et al\textsuperscript{26}</td>
<td>1 human</td>
<td>Diagnostic and ablation study</td>
<td>1.5</td>
<td>Passive</td>
</tr>
<tr>
<td>2013</td>
<td>Sommer et al\textsuperscript{27}</td>
<td>5 humans</td>
<td>Diagnostic study</td>
<td>1.5</td>
<td>Passive</td>
</tr>
<tr>
<td>2013</td>
<td>Nordbeck et al\textsuperscript{28}</td>
<td>1 mini pig</td>
<td>Diagnostic study</td>
<td>1.5</td>
<td>Passive</td>
</tr>
<tr>
<td>2014</td>
<td>Gaspar et al\textsuperscript{29}</td>
<td>1 swine</td>
<td>Diagnostic and ablation study</td>
<td>1.5</td>
<td>Active</td>
</tr>
<tr>
<td>2013</td>
<td>Piorkowski et al\textsuperscript{30}</td>
<td>1 human</td>
<td>Diagnostic and ablation study</td>
<td>1.5</td>
<td>Passive</td>
</tr>
<tr>
<td>2014</td>
<td>Grothoff et al\textsuperscript{31}</td>
<td>10 humans</td>
<td>Diagnostic and ablation study</td>
<td>1.5</td>
<td>Passive</td>
</tr>
</tbody>
</table>

![Differences between device tracking](image_url)

**Figure 2.** Different device tracking strategies. **A (Left),** Passive tracking, an approach using the susceptibility artifact (white arrows) for device visualization. **B (Right),** The active tracking approach using microcoils on the device resulting in multiple benefits including improved visualization update (achievable within a few milliseconds) and device-guided navigation. AAo indicates ascending aorta; IVC, inferior vena cava; RA, right atrium; and RV, right ventricle.
Pericardial Needles
Both passive and active needles have been studied in animals. A comparison between these needles demonstrates favorable results for active tracking. Active needles needed shorter access time (88 versus 244 s; \( P=0.022 \)) and required significantly fewer needle passes (4.5 versus 9.1; \( P=0.028 \)).

To summarize, recent technical improvements have resulted in the advent of MRI conditional (active trackable) electrophysiology tools, including needles, guidewires, and (multi-electrode) catheters.

Image Acquisition
Image acquisition for procedural guidance can be divided into 3 stages: (1) catheter navigation, (2) catheter tip localization before ablation, and (3) visualization and evaluation of lesions immediately after ablation. Mandatory sequences for this workflow (eg, steady-state–free precession, T2, and late gadolinium enhancement) are available for both 1.5 T and 3 T scanners. Although the various stages require different strategies (eg, high-quality low temporal resolution procedural roadmap versus low-quality high temporal resolution catheter navigation), a standardization of applied sequences and scanning approach is still lacking (Table 2).

Procedural Roadmap
The majority of studies conducted to date do not implement preprocedurally acquired roadmaps for electrophysiology and ablation procedures. This might be because of the limited number of studies investigating redo procedures or evaluating the substrate-based ablation of arrhythmias. A study in a porcine myocardial infarction model reported a good correlation of infarct location on late gadolinium enhancement images compared with a MRI-compatible EAM system–based voltage map. Preprocedural planning (anatomy and substrate imaging) is essential for complex arrhythmias and integration of these data in iCMR suites should be further investigated.

Catheter Navigation and Tip Localization
It has been observed that a frame-rate of \( \approx 5 \) frames/s is acceptable for catheter guidance in electrophysiology procedures. Currently, commercially available, real-time steady-state–free precession sequences provide frame rates ranging between 5 and 8 frames/s. The easy availability of these sequences facilitates passive tracking in every center with a diagnostic CMR scanner. This encourages clinical translation without a demand for major device modifications.

However, because of its inherent advantages and despite the current preclinical state of development, active tracking features are considered to be the method of choice for clinical electrophysiology and ablation in the near future.

Lesion Evaluation
A unique strength of CMR, compared with other imaging modalities, is the ability to perform tissue characterization. This can be used to identify and distinguish between the 2 cellular reactions that occur during an ablation: (1) acute (edema) and (2) permanent (necrosis). Both edema and necrosis can be evaluated using commercially available sequences, and quantitative high-resolution \( T_2 \)-mapping techniques in 2D and even in 3D can be used to visualize edema. Necrosis can be visualized using the commercially available T1-weighted phase-sensitive inversion recovery turbo–gradient recalled echo or using the experimental 3D respiratory-navigated inversion-recovery–gradient recalled echo sequence. Direct feedback during the ablation procedure may contribute to a complete isolation during the first attempt. In case there is reoccurrence of arrhythmias because of incomplete isolation, this information can be used to perform targeted gap ablation. Detailed MRI-derived information with respect to lesion formation has therefore the potential to improve single procedure success rates.

Table 2. Ablation Stages and Utilized Cardiac MRI Sequences

<table>
<thead>
<tr>
<th>Procedural Stage</th>
<th>Type Sequence</th>
<th>Availability</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preprocedural</td>
<td>T1-weighted PSIR turbo-GRE</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Substrate identifcation</td>
<td>MRA (3D respiratory navigated and ECG-gated GRE)</td>
<td>Commercial</td>
<td>24</td>
</tr>
<tr>
<td>Roadmap</td>
<td>3D self-navigation strategies</td>
<td>Commercial</td>
<td>41</td>
</tr>
<tr>
<td>Catheter guidance</td>
<td>Real-time balanced SSFP (8 fps)</td>
<td>Commercial</td>
<td>31</td>
</tr>
<tr>
<td>Catheter navigation</td>
<td>T1-weighted FLASH (5–6 fps)</td>
<td>Experimental</td>
<td>21, 23</td>
</tr>
<tr>
<td>Catheter tip at ablation site</td>
<td>Real-time balanced SSFP (8 fps)</td>
<td>Commercial</td>
<td>31</td>
</tr>
<tr>
<td>Ablation lesion</td>
<td>T2-weighted HASTE</td>
<td>Commercial</td>
<td>23</td>
</tr>
<tr>
<td>Edema</td>
<td>T2-weighted TSE</td>
<td>Commercial</td>
<td>31</td>
</tr>
<tr>
<td>High-resolution quantitative 2D and 3D ( T_1 )-mapping strategies</td>
<td>Experimental</td>
<td>42, 43</td>
<td></td>
</tr>
<tr>
<td>Necrosis</td>
<td>3D respiratory-navigated IR-GRE</td>
<td>Experimental</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>T1-weighted PSIR turbo-GRE</td>
<td>Commercial</td>
<td>31</td>
</tr>
</tbody>
</table>

3D indicates 3-dimensional; FLASH, fast low angle shot; fps, frames/s; GRE, gradient recalled echo; IR, inversion recovery; HASTE, half-fourier acquisition single-shot turbo spin-echo; MRA, MR angiography; PSIR, phase sensitive inversion recovery; SSFP, steady-state–free precession; and TSE, turbo spin echo.
Image Reconstruction
Implementing an iCMR suite is significantly different from the conventional diagnostic imaging set up and requires an optimization of the imaging workflow. Performing an interventional study requires (1) real-time acquisition and near real-time reconstruction, (2) rapid sequence changes, and (3) integration with device hardware for tracking purpose (Figure 3). It is has been shown that standard sequences, present on every diagnostic scanner, can be used for performing and evaluating interventions.31 However, there are 3 specifically designed visualization frameworks targeted at the electrophysiology community (ie, Gadgetron, Vurtigo, and RTHawk) that are user-friendly and can facilitate procedural guidance. An overview of these frameworks and their respective functionalities is provided below.

Gadgetron
Gadgetron is an open source, modular framework designed to facilitate rapid development and easier sharing of image analysis and reconstruction algorithms.44 Modules (gadgets) can be developed using standard toolkits present in the framework. These gadgets are programmed to perform specific post-processing tasks and can be configured as part of the scanner data pipeline. Multiple gadgets can be used for simultaneous processing. Furthermore, the individual gadgets can be reused in different workflows thereby enabling thorough evaluation of consistency and performance.

However, this dynamic framework does have a major limitation. There are no possibilities to control the MRI scanner directly using the tools provided. Therefore, image acquisition can only be performed using the existing scanner front-end. Because of the restrictions of the in-built interfaces, this will require deployment of third-party solutions.

Vurtigo
The visualization platform for real-time, MRI-guided cardiac electroanatomic mapping (Vurtigo) is another open source platform-independent application that provides useful features for interventional electrophysiology.45

The core of Vurtigo is the geometry server, a storage space containing images, plane orientations, and catheter information. Vurtigo can communicate directly with the scanner through a plugin (OpenIGTLink), allowing direct manipulation of the scan plane. In addition, this software tool also offers the possibility to integrate pre-existing electric anatomic mapping with acquired volume and tissue characterization images. This can facilitate the ablation by generating procedural roadmaps, incorporating anatomic information and tissue substrate.

RTHawk
RTHawk is an advanced development platform to design, simulate, and run MRI applications (sequences, reconstruction pipelines).46 In addition, there are possibilities for rapidly switching between different pulse sequences and performing real-time postprocessing. Furthermore, it also enables integration of the designed applications with external hardware, for example, interventional devices. Unfortunately, sparse information with respect to this platform is currently available.

Safety and Workflow in the Interventional MRI
The transition from conventional fluoroscopic procedures toward an iCMR suite requires revision of the existing workflow. Cath-laboratory personnel used to work in a fluoroscopic environment need education about operating in a magnetic field. Furthermore, patient monitoring and safety protocols require thorough revision and scenario training.

Architectural Layout
In contrast to conventional fluoroscopy-guided procedures, an intervention in the iCMR suite is bound to more strict rules. The procedures are performed in an environment that is less accessible for personnel because each step closer to the magnet increases the risk of ferromagnetic interaction. The design of an iCMR suite needs to incorporate various aspects considered daily practice for conventional interventions. This includes but is not limited to (1) patient preparation, (2) access to device storage, (3) sterility and air treatment, and (4) evacuation possibilities in case of an emergency. Each of these aspects needs to be carefully considered and adequately addressed.

Personnel
During the electrophysiology and ablation procedures, an experienced technician, radiologist, or imaging cardiologist needs to be present for image acquisition. During the development phase of an iCMR suite, it is advisable (if not mandatory) to have a knowledgeable physicist present for optimization of imaging sequences used during the procedures.

During the initial another potential role during interventions could be that of a safety officer. This person could be appointed as coordinator in case of emergency situations. Once a routine procedural workflow is achieved, a dedicated coordinator may become redundant.
Communication
An essential part of the ablation procedure is the communication between the electrophysiologists and the technician. The development during the past years has progressed rapidly with commercially available MR-compatible solutions (Optoacoustics, Clear-com, Gaven).

Headsets
Initial MR headsets used fiber optic cables and limited the working radius of the interventionalist. More recent technology offers wireless communication and supports multiple headsets. Optoacoustics uses infrared technology to full wireless coverage in both the scanning room and the control room.

Projection Systems
High-definition beamers can be shielded and installed in the iCMR. These commercially available systems offer a resolution of 1080p and can be configured to display multiple data streams.

Patient Safety
Telemetry
Conventional ablations rely on both intracardiac and surface ECG recorded during the intervention. However, surface ECG get distorted in the MRI because of the magnetohydrodynamic effect caused by the static magnetic field (B₀). Additional interference is caused because of the switching gradients and results in further deformation of the ECG signal. Such ECG artifacts can also lead to trigger problems and consequently suboptimal image quality.

There are currently no commercial solutions for 12-lead ECG monitoring in the MRI. Recent human studies have successfully demonstrated the feasibility of a custom-made 12-lead ECG acquisition during a CMR study. This is accomplished using custom-made filtering hardware and provides reliable ECG signals with a signal-to-noise ratio loss ≤5%. No adverse events, for example, electrode heating or surface burns were reported.

Sedation
Recent studies advocate the importance of sedation during complex ablative procedures (eg, atrial fibrillation, ventricular tachycardia). Sedation reduces patient discomfort and can result in shorter and more effective procedures. To operate under sedation, the intervention room set up requires basic anesthesia equipment, for example, ventilator, vital signs recorders (P₀₂, blood pressure, respiration), and ECG monitors.

Advanced MRI-compatible anesthesia equipment is available (Aestiva/5 MRI, Datex-Ohmeda, Madison, WI) and can be easily transferred into the iCMR environment.

Tamponade
Cardiac tamponade is a potentially life-threatening complication associated with ablative therapy. The incidence varies for the different interventions with numbers reported ≤6%. Current guidelines advise immediate echocardiography in case hypotension develops. Confirmation of this diagnosis is followed by pericardiocentesis to drain the excessive fluid from the pericardial space. Because of variations in the anatomy, this sometimes results in a complex procedure.

In conventional fluoroscopic rooms, this is best performed using echocardiography. In case of iCMR, there are various sequences that can diagnose and potentially locate the lesion. In addition, a recent animal study demonstrated the feasibility of performing pericardiocentesis inside the scanner room using commercially available needles. In total, 12 successful procedures (no complications) were performed using a real-time imaging approach and passive tracking of the needle. This development increases the practicability of complex ablative therapy in the scanner and significantly expands the emergency solving capacity of iCMR.

Specific Absorption Rate
The specific absorption rate indicates the amount of radiofrequency energy deposited in the tissue. The safety limit, as indicated by the Food and Drug Administration, for whole body—specific absorption rate is 4 W/kg per 15-minute exposure and should be monitored during the procedure. In case this limit is exceeded, scanning should be stopped to allow recovery of the tissue. In general, this situation can also be prevented by increasing the repetition time or reducing the flip angle.

Defibrillation
Performing electrophysiology procedures in an iCMR suite requires a meticulously constructed evacuation plan. This is especially required for patients on respiratory support and with a multitude of monitors attached. A possible solution could be integrating monitoring and ventilation with the scanner table. This would allow emergency cases to be rapidly shifted toward a room where defibrillation and other resuscitative actions can be performed without any restrictions.

Electric mapping of arrhythmias are performed by inducing the tachycardia by means of stimulation protocols. Especially in case of ventricular tachyarrhythmias, this can cause hemodynamic instability in patients and forces cardioversion to be performed. Currently, there is no solution allowing defibrillation to be performed inside an iCMR suite. In case of diagnostic scans, this has not been a limiting factor, as a patient can be transported out of the magnet within few seconds. This changes when a patient is instrumented with catheters and undergoing an ablation. In this particular scenario, even with the correct protocols in place, it is a challenging task to safely bring the patient outside the MR suite. Therefore, defibrillation should be considered as a major issue, which needs to be addressed before performing complex (ventricular) ablative procedures.

Clinical Perspective
The benefits of iCMR including 3D guidance, tissue characterization, and lack of radiation exposure over conventional fluoroscopic procedural guidance are the underlying rationale for researchers investigating the feasibility of iCMR (Table 1). Despite the growing number of centers experimenting with iCMR, the clinical translation remains a challenge.

An important reason is the limited availability of MRI-compatible devices (eg, needles, guidewires, catheters, and
In the recent years, both active and passive devices have been developed and tested (Table 1). Although active devices might be prone to heating issues, they offer multiple benefits over passive devices, including (1) real-time, device-guided navigation, (2) no artifact and loss of anatomic information in the surrounding tissue, and (3) easy distinction (using color coding) between electrodes and different devices. Future trials should focus at the design and heating aspects to enable active device usage in human studies.

Another major reason delaying clinical implementation is the comprehensive technical know-how required on both, the imaging and electrophysiology level. However, the fact that basic (human) ablation studies can already be performed successfully inside the MRI using passive devices indicates that the initial (difficult) pioneering phase has come to an end.31 The workflow (using commercial imaging sequences) and set up (MRI-compatible catheters and electrophysiology system) as described in this review has resulted in an increased interest from multiple institutions to explore iCMR for electrophysiology and ablation purposes.

A well thought out implementation strategy is essential before considering a transition toward iCMR. It seems obvious to start with relatively simple procedures such as right-sided heart catheterization.49,50 This serves 3 important goals: (1) to start with relatively simple procedures such as right-sided heart catheterization, (2) no artifact and loss of anatomic information in the surrounding tissue, and (3) easy distinction (using color coding) between electrodes and different devices. Future trials should focus at the design and heating aspects to enable active device usage in human studies.

Another major reason delaying clinical implementation is the comprehensive technical know-how required on both, the imaging and electrophysiology level. However, the fact that basic (human) ablation studies can already be performed successfully inside the MRI using passive devices indicates that the initial (difficult) pioneering phase has come to an end.31 The workflow (using commercial imaging sequences) and set up (MRI-compatible catheters and electrophysiology system) as described in this review has resulted in an increased interest from multiple institutions to explore iCMR for electrophysiology and ablation purposes.

A well thought out implementation strategy is essential before considering a transition toward iCMR. It seems obvious to start with relatively simple procedures such as right-sided heart catheterization.49,50 This serves 3 important goals: (1) familiarizing and educating the assisting personnel about the safety issues of working in an MRI environment, (2) training the radiographer to better understand the requirements (visualization planes) of the operating physician, and (3) allowing the interventionalist to get used to the benefits (no heavy lead protection) and limitations associated with procedures in the iCMR. Once the necessary experience is acquired, these procedures can be replaced by electrophysiological interventions with simple catheter set ups, for example, atrial flutter ablation. Before applying iCMR in complex ablations (atrial fibrillation and ventricular tachycardia), fundamental obstacles, for example, commercial 12 lead ECG system and defibrillation need to be resolved.

**New Challenges: Competitive Methods**

Besides the tissue characteristic–based road-map, noninvasively obtained inverse potential maps generated from body surface potential mapping may reduce procedural duration and improve outcome.51 Inverse potential map is already being applied to analyze complex arrhythmias and has great potential to generate personalized ablation strategies.32 The anatomic volume conductor models required to perform inverse potential map can also be used for preparing a patient-specific procedural roadmap (Figure 4).

Not only the required technical advances for the devices needed to conduct an electrophysiology or ablation procedures safely in an MRI environment will be crucial but also improved patient selection and therapy stratification will be essential. Integrating noninvasively obtained anatomic information with tissue characteristics and electric properties will remain a challenging field of research and development.

**Conclusions**

iCMR is an emerging technology and may play an important role in the future for the treatment of complex arrhythmias. The past decade has seen tremendous progress made in this field with relatively simple electrophysiology procedures being performed successfully in humans. However, there are still a few major challenges to overcome before performing complex ablation procedures in the MRI environment: (1) MRI-compatible equipment (12 lead ECG, catheters, and ablation systems) with regulatory approval is needed, and (2) emergency strategies especially on defibrillation inside the MRI have to be established. The coming years should be targeted at resolving these issues to expedite the clinical transition of ablation procedures toward iCMR. Finally, the complete integration of noninvasively obtained anatomic data with tissue characteristics and its electric behavior will demonstrate the full strength of such an iCMR approach.

**Disclosures**

None.

**References**


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