Because of its wide availability, echocardiography is the most frequently used modality for diagnosis of the underlying substrate for cardiac arrhythmia. However, echocardiography is unable to visualize intramyocardial substrates for reentrant arrhythmia such as fat or scar fibrosis. Replacement of myocytes with nonviable tissue results in hypertrophy of the remaining viable cells and is associated with altered ion channel and gap junction expression. These changes affect myocardial mechanical function and promote arrhythmia. Because of its soft-tissue resolution, multiplanar imaging capabilities, and specialized techniques uniquely suited for diagnosis of various structural changes, cardiac magnetic resonance (CMR) offers significant advantages for identification of arrhythmic substrates.

Ischemic cardiomyopathy (ICM) is ventricular dysfunction resulting from coronary artery disease and myocardial infarction and is a common substrate of ventricular arrhythmia. Techniques to visualize infarcted myocardium in the acute and chronic settings have been well described and rely primarily on steady-state free precession cine CMR for evaluation of function, and late gadolinium enhancement (LGE) imaging to assess scar burden and distribution. The steady-state free precession cine technique relies on short repetition times and electrocardiographic gating to provide dynamic visualization of the heart during the full cardiac cycle. The LGE technique uses an inversion recovery gradient echo sequence with optimization of the inversion time set to null the signal of normal myocardium. In the setting of ICM, images are acquired 10 to 15 minutes after intravenous administration of 0.2 mmol/kg gadolinium chelate. Gadolinium chelates are hydrophilic and have low molecular weights thereby concentrating into the extracellular fluid space. The extent of LGE is primarily determined by expansion of the extracellular space in fibrotic tissue, which slows washout of the gadolinium chelates. This “delayed” time period from contrast administration to scan acquisition allows clearance of the contrast medium from the normal myocardium, whereas nonviable myocardium shows LGE due to enhanced relaxivity of excited protons adjacent to retained gadolinium, which increases the signal on T1-weighted images.

Hypertrophic cardiomyopathy (HCM) is characterized by myocardial hypertrophy resulting from an inherited defect in the protein components of the cardiac sarcomere. In cases where hypertrophy occurs at the basal septum, subaortic outflow obstruction and mitral regurgitation due to systolic anterior motion of the anterior leaflet of the mitral valve can be present. Echocardiography is the standard technique for evaluation of HCM. CMR is an appropriate alternative to confirm the diagnosis or identify atypical cases and is most useful when the echocardiography acoustic window is limited. LGE can detect midwall and patchy scar in regions with hypertrophy (Figure 1A). Necropsy studies have revealed good correlation between the LGE pattern of enhancement and the distribution of scar.

Nonischemic cardiomyopathy (NICM) is characterized by ventricular dilatation and impaired contraction in the absence of flow limiting coronary disease. Although some cases are due to viral, genetic, toxic, or immune causes, many are of unknown etiology. The anatomic and functional abnormalities of NICM are readily assessed by cine CMR. Midwall striae or patches of LGE can be identified in approximately one third of patients (Figure 1B). Compared with ICM, the pattern and location of LGE in NICM is often atypical, making it difficult to distinguish artifact from true scar. The presence of scar should, therefore, be verified by use of multiple image planes and optimized inversion times.

Sarcoidosis with cardiac involvement is relatively uncommon (<5% of patients with pulmonary sarcoidosis). Currently used techniques, including echocardiography, scintigraphy, and myocardial biopsy are often inadequate for early diagnosis. In patients with systemic sarcoidosis suspected of cardiac involvement, CMR may provide a diagnostic alternative and a method by which disease activity can be followed. Because of increased T2 relaxation time, inflammatory sarcoid granules present as high signal intensity regions on T2-weighted images. Focal areas of LGE likely representing fibrosis can be noted (Figure 1C), most commonly in the basal segments of the left ventricle (LV).

Arrhythmogenic right ventricular dysplasia (ARVD) is characterized by enlargement, dysfunction, and fibro-fatty infiltration of the right ventricle (RV). Given its ability to comprehensively image the RV and characterize fibro-fatty infiltration, CMR has emerged as an important adjunct for the diagnosis of ARVD. CMR abnormalities in ARVD can
be divided into functional and morphological abnormalities. \textsuperscript{35} Functional abnormalities include regional wall motion abnormalities, focal aneurysms, RV dilation, and/or systolic and diastolic dysfunction and are best evaluated via steady-state free precession cine imaging of the entire RV in axial or long-axis stacks. Substantial normal RV variations, including reduced wall motion near the moderator band, variable trabeculation, and fat deposits surrounding the coronary vessels and epicardium can limit interpretation for the non-experienced observer. \textsuperscript{36–38} Morphological abnormalities include fatty infiltration, focal wall thinning or hypertrophy, moderator band hypertrophy, RV outflow tract enlargement, and LGE involving both the RV and LV (Figure 1D). Importantly, LGE for assessment of scar in the RV must be performed with optimization of the inversion time for myocardial signal suppression for the RV, which is often substantially different than that optimized for the LV. \textsuperscript{39} Intramyocardial fatty infiltration can be observed as an area of high signal intensity on T1-weighted images. However, the normal presence of fat in the atrioventricular groove and anteroapical RV epicardium, and artifacts due to motion, arrhythmia, and surface coil proximity can substantially reduce the specificity of high T1 signal intensity for the presence of intramyocardial fat. \textsuperscript{40} It is also important to emphasize that identification of RV fat signal by imaging is not unique to ARVD, or a recognized criterion for its diagnosis. The contribution of CMR to ARVD diagnostic criteria are primarily through functional assessments such as regional RV wall motion abnormalities, dilatation, and aneurysms (Table 1). \textsuperscript{41}

Acute inflammatory myocarditis can accompany systemic immune dysfunction or exposure to pathogens and toxins. Endomyocardial biopsy, the gold standard for diagnosing myocarditis, is limited by inadequate sensitivity and specificity. \textsuperscript{42} LGE with early imaging (1 to 2 minutes) can show relative myocardial enhancement compared with skeletal muscle, likely due to the loss of cellular membrane integrity and accumulation of gadolinium chelates. \textsuperscript{43} Abnormal myocardial signal may also be present with T2-weighted images, and is a result of interstitial edema that increases the T2 relaxation time. Normalization of signal intensity occurs with healing, unless cell death has occurred, in which case LGE may show patchy enhancement. LGE 2 to 4 weeks after the onset of symptoms can predict functional and clinical long-term outcomes. \textsuperscript{43–45} Consistent with postmortem studies, LGE is often observed in the epicardium of the lateral free wall. \textsuperscript{46}

\begin{table}[h]
\centering
\caption{Summary of Current Diagnostic Criteria for ARVD. The Diagnosis of ARVD Is Fulfilled by the Presence of Two Major, or One Major Plus Two Minor Criteria, or Four Minor Criteria From Different Groups\textsuperscript{41}}
\begin{tabular}{ll}
\hline
I. Global and/or regional dysfunction and structural alterations & \\
Major & Severe dilatation and reduction of RV ejection fraction with no LV impairment \\
       & Localized RV aneurysms \\
       & Severe segmental dilatation of the RV \\
Minor & Mild global RV dilatation and/or ejection fraction reduction with normal LV \\
       & Mild segmental dilatation of the RV \\
       & Regional RV hypokinesia \\
II. Tissue characterization of wall & \\
Major & Fibrofatty replacement of myocardium on endomyocardial biopsy \\
Minor & \\
III. Repolarization abnormalities & \\
Minor & Inverted T waves in right precordial leads (V2 and V3) in people aged >12 yr, in absence of right bundle-branch block \\
IV. Depolarization/conduction abnormalities & \\
Major & Epsilon waves or localized prolongation (>110 ms) of the QRS complex in right precordial leads (V1 to V3) \\
       & Late potentials (signal-averaged ECG) \\
V. Arrhythmias & \\
Minor & Left bundle-branch block type VT \\
       & Frequent ventricular extra-systoles (>1000/24 h) by Holter \\
VI. Family history & \\
Major & Familial disease confirmed at necropsy or surgery \\
Minor & Family history of premature sudden death (<35 yr) due to suspected RV dysplasia \\
       & Familial history (clinical diagnosis based on present criteria) \\
\hline
\end{tabular}
\end{table}

ARVD indicates arrhythmogenic right ventricular dysplasia; RV, right ventricle.
Chagas disease is an inflammatory disease caused by the parasitic protozoan *Trypanosoma cruzi*. Although most patients survive the acute phase of the disease and remain asymptomatic for many years, 20% eventually present with heart failure. CMR can accurately assess morphological and functional aspects of cardiac involvement in Chagas disease.47

Surgical scar can serve as an anatomic barrier for arrhythmic reentry. CMR is capable of delineating cardiac structure and function postcardiac surgery, a setting where echocardiography is often hindered because of chest wall changes that diminish the acoustic window. LGE has been shown to identify fibrous tissue in the postsurgical myocardium.48 Atrial scar may occur in the setting of any of the above myopathies or in isolation.49 Although LGE imaging has been well established for detection of fibrosis in ventricular myocardium, imaging of scar in the atrium has proved challenging due to reduced wall thickness and the resulting requirement for higher spatial resolution. Recent studies have suggested a potential role for detection of atrial scar using LGE after pulmonary vein isolation procedures for atrial fibrillation (Figure 2, from Peters et al).50,51

### Applications of CMR for Arrhythmic Risk Assessment

Traditional techniques for arrhythmic risk assessment primarily rely on the clinical history, electrocardiographic features, morphological evaluation of ejection fraction or wall thickness by echocardiography, and electrophysiology study results. The mechanism of arrhythmia is often reentry or the propagation of activation around a barrier to conduction. This reentrant circuit is often complicated, involving parts or combinations of viable tissue channels delineated by scar islands (Figure 3). CMR is capable of imaging nonviable tissue and may identify potential substrates for reentry. Several recent studies have highlighted a role for CMR to complement traditional approaches for risk stratification of ventricular arrhythmia. These studies have been summarized below and in Table 2.

ICM patients suffer from elevated risk of ventricular arrhythmia, and have been shown to derive survival benefit from implantable cardioverter defibrillators (ICD).52–54 Bello et al showed that out of 48 patients referred for electrophysiology study, 18 with monomorphic ventricular tachycardia (VT) had larger infarcts than the 21 patients without inducible VT. Interestingly, 9 patients with inducible polymorphic VT or ventricular fibrillation had intermediate infarct mass. In logistic regression models including both infarct mass and LV ejection fraction, or both infarct surface area and LV ejection fraction, infarct mass, and surface area were the only significant predictors of inducible VT.55 Yan et al examined the extent of peri-infarct zone quantified by LGE as a predictor of mortality in patients with history of ICM. The authors found that out of 144 patients with coronary artery disease and LGE, those with above median ratio of peri-infarct zone extent (area of LGE region with intensity >2 but <3 SDs above null myocardium) to infarct extent (area of LGE region with intensity >3 SDs above null myocardium) had higher mortality. After adjusting for age and LV ejection fraction, peri-infarct zone extent to infarct extent ratio remained predictive of all cause and cardiovascular mortality.56 Schmidt et al also studied the utility of an LGE measure of peri-infarct tissue heterogeneity (defined as the myocardium with signal intensity more than peak remote signal intensity but <50% of maximal signal intensity of the manually contoured high signal intensity myocardium) in 47 patients referred for prophylactic ICD implantation for ICM. The authors found that higher tissue heterogeneity at the infarct periphery was predictive of inducible VT and that it was the only significant predictor in a stepwise logistic regression model containing infarct location and core extent, and LV ejection fraction and end-diastolic volume.57 These studies provide evidence that LGE may provide additional benefit for risk stratification of patients with ICM. A prospective study to determine the benefits of ICD implantation in patients stratified by infarct morphology identified by LGE is currently underway.58

HCM patients are at significant risk for sudden death; therefore, accurate and early risk stratification is essential in
this condition. Therefore, it is plausible that the extent of myocardial fibrosis in this disease may predict the occurrence of ventricular arrhythmia. Teraoka et al performed CMR examinations in 59 patients with HCM and noted that the presence and extent of LGE were directly correlated with the presence of nonsustained VT (NSVT) on Holter monitoring. Dimitrow et al also assessed LGE imaging in patients with HCM and found lower likelihood of LGE in patients without NSVT compared with those with NSVT. However, the extent of scar was not significantly different between the 2 groups in the study of Dimitrow et al. Later, Adabag et al performed LGE imaging on 177 patients with HCM and found that NSVT was more common in patients with LGE, and that patients with LGE had greater numbers of NSVT episodes. Similar to the findings of Dimitrow et al, however, the extent of LGE was similar in patients with and without NSVT. These findings suggest a potential utility of CMR for risk stratification of patients with HCM.

NICM commonly presents with atrial and ventricular arrhythmias. However, syncope and sudden death are rarely the initial manifestations of the disease. Current guidelines propose ICD implantation for prevention of sudden death in NICM patients with LV ejection fraction <35% and symptoms of heart failure. Our group performed LGE imaging before electrophysiology study in 26 patients with NICM and found that midwall myocardial enhancement involving >25% of wall thickness predicted inducibility of VT. Assomull et al enrolled 101 patients with NICM and found that midwall fibrosis, which was present in 35% of patients, predicted the combined end point of all cause death or hospitalization. Midwall fibrosis was also predictive of the combined end point of sudden death and VT after adjusting for LV ejection fraction. Similarly, Wu et al found that the presence of LGE in the setting of NICM predicts the composite end point of hospitalization for heart failure, appropriate ICD firing, and cardiac death. Identification of scar fibrosis may assist NICM patient selection for ICD implantation, and help direct VT ablation mapping efforts toward the site of scar related reentry.

Sarcoidosis involving the heart is uncommon, but sudden death due to arrhythmia may be its initial clinical presentation. Accurate diagnosis is essential as ICD implantation and early immunosuppressive therapy may improve prognosis. The capability of LGE to identify cardiac sarcoidosis suggests utility for risk stratification in this condition.

ARVD may be responsible for 10% to 20% of sudden cardiac deaths among certain populations. Tandri et al performed LGE imaging and electrophysiology testing in 30 patients being evaluated for ARVD. Sustained VT was inducible in 6 of 8 patients with LGE, whereas none of the patients without LGE had inducible VT. Although the long-term prognostic significance of this finding remains to be validated, it suggests that LGE has a potential role in risk stratification of patients with ARVD.

Acute inflammatory myocarditis can present with refractory VT, torsade de pointes, or sudden cardiac death. Refractory atrial fibrillation has also been associated with inflammatory infiltrates in the atrium. The role of CMR for arrhythmia management has not been assessed in acute myocarditis.

Chagas disease is commonly associated with VT often presenting during or after exercise. Importantly, arrhythmia may develop before cardiomegaly and heart failure are detected. Atrial arrhythmias, including atrial fibrillation have also been reported. Rochitte et al performed LGE imaging and electrophysiology testing in 30 patients with Chagas disease. The presence of LGE predicted inducible VT. However, the extent of scar was not significantly different between the 2 groups in the study of Dimitrow et al.
imaging in 51 patients with Chagas disease and found fibrosis detectable by LGE in 100% of patients with previously documented VT. This study suggests a potential role for use of CMR for prospective risk stratification in Chagas disease.

Surgical scar can be associated with reentrant arrhythmias including atrial tachycardia after atriotomy83–85 and VT after ventriculotomy or patch repair.86,87 CMR can be used to characterize the anatomy and assess scar burden thus aiding risk stratification and preprocedural planning, and is particularly useful in the case of complex postsurgical congenital heart disease.

Atrial scar extent and distribution detected by LGE has been associated with atrial arrhythmias.49 Recent studies have also suggested that postpulmonary vein isolation LGE may detect the extent of radiofrequency-induced damage in the atria.51 The extent of atrial scar seems to be inversely correlated with left atrial function88 and seems to be directly correlated to the success of atrial fibrillation ablation. The role of CMR in detecting atrial scar remains experimental, and future studies to determine its potential utility toward management of atrial arrhythmia are warranted.

**Applications of CMR for Catheter Ablation**

Introduction of electroanatomic mapping systems with the capability to merge preacquired images with procedural catheter positions and intracardiac voltage and activation sequence maps has led to rapid integration of CMR and computed tomography images into the clinical electrophysiology laboratory. Preacquired CMR images are commonly used to provide a “shell” of the endocardial/epicardial boundaries of cardiac chambers and other anatomic regions of interest such as the aortic root and coronary vessels. This capability has been particularly useful in atrial fibrillation ablation, where knowledge of the pulmonary vein anatomy can help avoid complications due to inadvertent ablation too far inside the vein or at the ostium of smaller variant branches.89 In addition, by providing the locations of the left atrial appendage and esophagus, image integration may reduce the potential of appendage perforation or esophageal damage.90 However, this technique may be limited by cardiac phase differences or movement of the esophagus compared with its position on the preacquired image.91 Software upgrades to enable integration of LGE images into the electroanatomic system are under development and will likely reduce procedural time devoted to voltage mapping in VT. Importantly, such a capability may also allow the delivery of lesions targeted near midwall scar not otherwise identifiable via endocardial or epicardial voltage mapping.

Ultimately, preacquired image integration may be replaced by real-time CMR guidance of electrophysiology procedures. However, catheter guidance by real-time CMR may be limited by catheter heating,92 current induction,93 image distortion,94 and electromagnetic signal interference.95 We have recently reported the feasibility of performing electrophysiology studies with real-time CMR guidance.96 In our study, heating, current induction, and signal interference were
mitigated by using nonferromagnetic catheters, radiofrequency filters, and limiting the specific absorption rate of CMR sequences. Image distortion was minimized by shortening of the echo time and the use of spin echo and fast spin echo CMR sequences. We demonstrated successful anatomic targeting of catheters and comprehensive electrophysiology studies with recording of intracardiac electrograms and pacing in the CMR environment. The capabilities of real-time CMR guidance for superior resolution of anatomic soft tissues, identification of scar arrhythmia substrates, and monitoring of lesion formation within linear sets and with respect to surrounding structures may improve the safety and efficacy of complex electrophysiology procedures.

Safety Considerations

Patients with cardiac arrhythmia often have high acuity of disease associated with decreased renal function, or ferromagnetic implants such as pacemaker or ICD systems as potential CMR contraindications. Recent studies have raised the possibility of gadolinium induced nephrotoxicity, and nephrogenic systemic fibrosis (progressive and severe fibrosis of the skin and other organs) in patients with advanced kidney disease. Current guidelines recommend avoidance of gadolinium chelates in patients with estimated glomerular filtration rate <30 mL min⁻¹ 1.73 m⁻². Ferromagnetic materials in a magnetic field are subject to force and torque. The radio-frequency and pulsed gradient magnetic fields of CMR may induce electric currents in leads and other ferromagnetic wires within the field. Radio-frequency pulses may also lead to implant heating and tissue damage at the device-tissue interface. In addition, sophisticated electronic implants, such as those in neurostimulators, pacemaker and ICD systems have the potential for electromagnetic interaction in the MRI environment, resulting in programming changes or loss of function. However, techniques for safe imaging with CMR in the setting of permanent pacemaker and ICD systems have been developed. Familiarity with CMR contraindications and implantable device classes with potential for electromagnetic interaction are essential for cardiologists performing examinations in this population of patients. The reader is encouraged to consult web sites that provide more specific information regarding individual devices (eg, www.mrisafety.com) for specific device testing details. In addition, current guidelines recommend avoidance of CMR during the first 3 months of pregnancy because of potential tissue heating, acoustic fetal damage, and teratogenic effects of gadolinium. Given the potential risks, it is important to conduct a systematic review of the patient’s condition, implanted devices, and safety for CMR. At our institution, all patients are asked to review and answer a safety questionnaire (Table 3).

Conclusion

CMR is increasingly recognized as an important imaging adjunct for the diagnosis of arrhythmogenic myocardial substrates. Advances in CMR, electroanatomic mapping technologies with LGE image integration, and real-time CMR guidance of electrophysiology procedures will likely facilitate arrhythmic risk stratification and complex arrhythmia procedures.

Disclosures

Dr Halperin serves as scientific advisor for Boston Scientific Inc and holds a patent on MRI compatible catheter technology. Dr Bluemke has received honoraria from General Electric Healthcare for lectures. The Johns Hopkins University Advisory Committee on Conflict of Interest manages all commercial arrangements.

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