The Value of Magnetic Resonance Imaging in Catheter Ablation of Atrial Fibrillation

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ABSTRACT

Atrial fibrillation (AF) is the most common arrhythmia encountered in clinical practice. Catheter ablation is now a recognized treatment for those with symptomatic AF refractory to drug therapy. Innovations in magnetic resonance imaging (MRI) have empowered clinicians to improve ablation efficacy while reducing the risk of complications. It is demonstrated that late gadolinium enhancement MRI has additional advantages over modalities such as echocardiography and computed tomography, due to its ability to assess the structural remodeling directly. As a result, MRI has become an indispensable imaging tool to personalize the AF ablation strategy, assess the efficacy and potential complications of AF ablation, and guide the repeat procedure.

Introduction

Atrial fibrillation (AF) is the most common type of arrhythmia in clinical practice and a major cause of morbidity and mortality due to increased risk of abnormal hemodynamics and thromboembolism.¹ The advent of catheter ablation has been established as an important therapeutic alternative in patients with drug-refractory and symptomatic AF, and in selected instances this procedure is now considered first-line therapy.² Although ablation for AF has a safety profile that is improving, considerable issues with complications and patient safety persist, and strategies to maximize ablation efficacy and minimize the need for further ablation attempts are of obvious importance. Recently, innovations in magnetic resonance imaging (MRI) have been applied to improve ablation efficacy while reducing the risk of complications. Late gadolinium enhancement MRI (LGE-MRI) has additional advantages over modalities such as echocardiography and computed tomography (CT) due to its ability to assess the atrial structural remodeling and scar burden directly.^{3–5} Scar burden has been used to predict ablation efficacy and the site of pulmonary vein (PV) reconnection in patients who

have undergone initial AF ablation.^{4,5} This article discusses the value of MRI in catheter ablation for AF patients.

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Personalizing the Strategy of Atrial Fibrillation Ablation

Currently, AF ablation strategy is closely associated with AF clinical phenotype. Pulmonary vein isolation (PVI) guided by 3-D mapping systems (Carto [Biosense Webster Inc., Diamond Bar, CA] or EnSite [Endocardial Solutions, St. Jude Medical Inc., St. Paul, MN]) is the major ablation type for paroxysmal AF, and additional substrate modification is required for persistent or chronic AF.⁶ Left atrium (LA) and PV anatomy assessed by MRI has become the most widely accepted prior to AF ablation, which appears to provide detailed anatomic and quantitative information.⁷ It is illustrated that LA dimension is strongly related to the clinical outcome of catheter ablation in AF. Compared with other imaging modalities such as transthoracic echocardiography (TTE) and cardiac CT, MRI has additional advantages to assess the LA dimension. Despite its higher temporal resolution, TTE regularly underestimates LA dimension by 15 to 30 mL as a consequence of reduced image quality.^{8,9} Moreover, TTE also has interobserver variability that is twice as high when compared with cardiac MRI or CT.^{8,9} Meanwhile, cardiac CT makes a small yet significant overestimation of LA maximal dimension when compared with cardiac MRI.^{8,10} This difference is augmented in examinations performed during AF.⁹ Therefore, despite a lower spatial resolution

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than CT and a lower temporal resolution compared with echocardiography, cardiac MRI seems to be the most ideal modality for the assessment of LA dimension.

Nowadays, the recurrence rate following ablation continues to present an ongoing challenge, with need for repeat ablation procedures in anywhere between 20% and 50% of patients. Atrial tissue fibrosis is independently associated with likelihood of recurrent arrhythmia.^{11,12} It has been demonstrated that AF clinical phenotype and AF-related fibrotic changes or atrial disease progression are not equivalent. For example, patients with a short known history of paroxysmal AF could have extensive atrial fibrosis; and, conversely, patients diagnosed with persistent AF for many years could have a minimal amount of fibrosis. Mild LA fibrosis by LGE-MRI predicts favorable LA structural and functional reverse remodeling and long-term success after catheter ablation of AF, irrespective of the paroxysmal or persistent nature of AF.¹³ Hence, the current strategy of AF ablation probably needs to be improved.

Recently, LGE-MRI has been applied to screen for the presence of LA fibrosis and to guide the ablation strategy in these patients.^{12,14,15} Left atrial fibrosis quantification can be used to assign the degree of LA fibrosis into 4 quartiles⁹: Utah stage I (<10%), Utah stage II (10%–20%), Utah stage III (20%–30%), and Utah stage IV (>30%). Akkaya et al¹⁴ found that the degree of LA structural remodeling (LASRM) detected using LGE-MRI was a predictor for procedural success in patients undergoing AF ablation. In the DE-MRI Determinant of Successful Radiofrequency Catheter Ablation of Atrial Fibrillation (DECAAF) multicenter, prospective, observational cohort study,¹² atrial fibrosis estimated by LGE-MRI was independently associated with likelihood of recurrent arrhythmia in patients undergoing AF ablation. Patients with minimal LASRM (Utah stage I) had excellent results after AF ablation, whereas poor results were obtained in patients with extensive LASRM (Utah stage IV). Ablation therapy (PVI and posterior wall debulking) would be applied for all patients in Utah stages I and II, and also for patients with localized fibrosis in Utah stage III. For Utah stage III patients with diffuse fibrosis, however, pharmacotherapy, including anticoagulants, would be given instead of ablation therapy. All patients in Utah stage IV would be treated only by medication (Figure 1). In another study, ablation outcome was best predicted by advanced structure remodeling stage identified on LGE-MRI, and extensive LGE ($\geq 30\%$ LA wall enhancement) predicted poor response for catheter ablation therapy of AF.¹⁵ Therefore, the degree of LA wall fibrosis estimated by LGE-MRI has the potential to offer a noninvasive and effective method for determining which patients with AF are likely to benefit from catheter ablation while avoiding performing procedures in patients likely to have arrhythmia recurrence.

Cardiac MRI T1 mapping is an alternative method to measure myocardial fibrosis and has been used to assess fibrosis in the ventricles.¹⁶ It has been shown that an inverse linear relationship exists between contrast-enhanced left ventricular (LV) myocardial T1 time and the burden of global myocardial fibrosis. Neilan et al demonstrated that the myocardial extracellular volume in the left ventricle detected by T1 mapping was the strongest predictor in the best overall model for recurrent AF post-PVI.¹⁷ Recently, a

Figure 1. Chart showing treatment for AF according to Utah classification. Abbreviations: AF, atrial fibrillation; LGE-MRI, late gadolinium enhancement magnetic resonance imaging.

study showed that cardiac MRI T1 mapping for noninvasive tissue characterization of the LA wall was feasible. Left atrial T1 relaxation times were significantly lower in patients with AF vs healthy volunteers. Left atrial T1 times were also lower in patients with AF with prior ablations vs patients with AF without prior intervention, suggesting the presence of increased fibrosis after ablation.¹⁸ In contrast to the LGE-MRI technique, which identifies focal and cohesive fibrosis, T1 mapping can detect and quantify the extent of global diffuse interstitial myocardial fibrosis. However, LA T1 mapping is significantly limited by partial volume effect of current T1-mapping techniques.

Detecting Left Atrial Appendage Thrombus Before Atrial Fibrillation Ablation

Stroke may result from embolization of a preexisting LA appendage (LAA) thrombus by catheter manipulation or with restoration of sinus rhythm. Therefore, the presence of LAA thrombus is a contraindication to catheter ablation of AF. Transesophageal echocardiography (TEE) is the most sensitive and specific technique for detecting LAA thrombus. However, TEE carries some risk, is a relatively expensive procedure, and can extend the length of hospital stay. The recognized complication rate during TEE examination is 0.88% and includes bleeding, perforation, conscious sedation/anesthesia-related events, hypotension, cardiac arrhythmia, and death.¹⁹ Noninvasive alternatives to TEE for the identification of LAA thrombus hold the promise of decreasing health care costs and avoiding invasive complications. In a cardiac MRI study by Ohyama et al,²⁰ it was reported that, compared with TEE, MRI had a higher reproducibility in detecting LAA thrombus in patients with AF and a history of stroke. If gadolinium contrast is applied during the MRI protocol before catheter ablation evaluation, it will allow enhanced tissue characteristics to better differentiate LAA wall, thrombus, and flow-related features. A recent study indicated that contrast-enhanced cardiac MRI offered a comparable and equally specific alternative to TEE for the complete noninvasive evaluation of LAA thrombus.²¹ Although not proven in a randomized fashion, this suggests that cardiac MRI examination ensures adequate coverage of the LAA and may potentially substitute for TEE in patients eligible for cardiac MRI, without a reduction in diagnostic yield. But on the other hand, TEE is usually performed at the time of ablation and MRI is

performed some time prior to ablation; therefore, a window of time is present that can miss the formation of LAA thrombus, which may increase the risk of thromboembolism and stroke to some extent.

Evaluating the Efficacy of Atrial Fibrillation Ablation and Guiding Repeat Procedures

Recent studies demonstrated that cardiac MRI could identify the extent of LA scarring present at 3 months postablation, that patients with more extensive scarring had a lower AF recurrence rate,^{4,5} and the value of cardiac MRI in postablation imaging would be for identification of regions around the PVs where scar was incomplete, with a view to guiding repeat ablation procedures. Badger et al observed that LGE-MRI could accurately depict the location and extent of scar lesions based on the correlation of these lesions with low-voltage LA regions on electroanatomic mapping. This group also demonstrated that LGE-MRI could be used to identify the location of breaks in ablation lesions, which correlated with recovery of electric conduction that could be responsible for AF recurrence after ablation.²² However, other studies have been less encouraging. Although Spragg et al also observed a significant association between scar identified by LGE-MRI and LA low-voltage regions on electroanatomic mapping, they found no association between MRI scar gaps and mapped PV reconnection sites.²³ More disappointingly, a study in 50 paroxysmal AF patients undergoing either wide-area or ostial ablation suggested that LGE-MRI imaging of LA myocardium was not accurate in detecting ablation lesions.²⁴ Inability to detect ablation lesions means the loss of ability to predict recurrent AF, and LGE-MRI is therefore unlikely to assess the efficacy of catheter ablation.

Although the reasons for the wide variation in reported results remain unclear, in part this may relate to methodology. Diagnostic accuracy of LGE-MRI is still unsatisfactory, which is affected by several factors, including limited image resolution, motion or flow artifacts, and volume averaging in LGE-MRI imaging of fibrosis. This likely reflects the presence of small bundles of viable myocardium, too thin to detect with current LGE-MRI resolution.²⁵ On the other hand, currently atrial scarring is identified by a bipolar voltage of ≤ 0.05 mV—this threshold originates from the baseline noise in early electroanatomic mapping systems and has been propagated through the literature and clinical practice without published pathological validation. But a recent experimental study indicated that the mean bipolar voltage at the center of the ablation line was 0.6 mV acutely and 0.3 mV chronically.²⁶ These values would suggest that using a threshold of ≤ 0.05 mV to define atrial scar could significantly underestimate the extent of previous ablation injury, perhaps leading to inaccurate interpretation of voltage data and not corresponding to MRI scar gaps. Accordingly, at least at this time, cardiac MRI does not have direct, real-time visualization capability to localize gaps.

Assessing the Complications of Atrial Fibrillation Ablation

A variety of complications are associated with AF ablation, ranging from vascular-access complications to potentially

life-threatening complications such as stroke, PV stenosis, and atrioesophageal fistula formation. Nowadays, the rate of PV stenosis following AF ablation is declining; nonetheless, it remains a clinical entity with potentially significant implications for the affected patient. Magnetic resonance imaging and CT have been the most commonly employed modalities to diagnose patients who have PV stenosis.²⁷ The main advantage of MRI over CT obviously relates to the avoidance of radiation exposure.

Esophageal tissue injury (ETI) is a potential precursor of atrioesophageal fistula formation and results from a collateral thermal effect of radiofrequency ablation on the posterior aspect of the adjacent LA.^{28–30} Esophageal endoscopy is the gold standard for visualizing ETI following LA ablation. However, this invasive procedure is associated with potentially serious complications and thus may not be applicable as a screening method to detect ETI in asymptomatic patients. Recently, LGE-MRI has proved useful for the detection of significant esophageal injury as indicated by the presence of anterior esophageal enhancement. In a prospective study of patients undergoing AF ablation, 5 of 41 patients (12.2%) had anterior esophageal wall enhancement within 24 hours of ablation. Three of these 5 patients had follow-up LGE-MRI within 1 week of ablation, at which time the esophageal enhancement had resolved. The postablation cardiac LGE-MRI protocol has been useful in practice to identify those patients at risk of atrioesophageal injury and ensure appropriate follow-up until complete esophageal healing has occurred.³¹ However, another study indicated that LGE-MRI of the esophagus was not a reliable screening method due to false-positive (12%) findings, compared with esophageal endoscopy.³² So the diagnostic accuracy of LGE-MRI for ETI still needs improvement.

Monitoring the Recovery of Atrial Function and Reverse of Atrial Remodeling After Atrial Fibrillation Ablation

Catheter ablation of AF is often associated with sustained atrial dysfunction due to ablation-related scarring. Cardiac MRI offers noninvasive assessment of atrial injury and recovery of active atrial function following AF ablation^{33–35} due to its ability to visualize all segments of the atrial wall during the cardiac cycle. Cardiac MRI demonstrated reversibility of LA, LAA, and right atrial dysfunction associated with resorption of periatrial edema after successful ablation of persistent AF.³³ Additionally, cardiac MRI was applied to assess the impact of sinus-rhythm restoration on reverse LA remodeling using serial follow-up examinations during a 1-year period after PVI. Pulmonary vein isolation-based restoration of sinus rhythm led to a significant and progressive decrease of LA diastolic and systolic volumes during 1 year, as assessed by direct volumetric MRI.³⁵

Magnetic Resonance Imaging Fusion

Due to the complexity of LA and PV anatomy, the integration of 3-D LA imaging (CT or MRI) with its corresponding electrical map into 1 hybrid fused image has gained popularity, given its potential to simplify the ablation procedure. The fusion of imaging technologies recently

has been reviewed and includes CartoMerge (Biosense Webster), the NavX Fusion system (St. Jude Medical), and others. Early studies comparing ablation procedures using conventional fluoroscopy vs the image-integration approach report a lower arrhythmia recurrence rate for the image-integration group.^{36,37} A more recent study showed that hybrid imaging with cardiac MRI did reduce fluoroscopy time but did not affect procedural duration time or freedom from recurrence.³⁸ Despite the limited number of patients studied, these data demonstrate the importance of electroanatomic mapping combined with 3-D imaging.

A recent study comparing intracardiac echocardiography (ICE) to MRI integration to guide ablation showed that ICE integration significantly reduced fluoroscopy time as compared with cardiac MRI and that the addition of MRI to ICE did not reduce procedural duration or x-ray exposure.³⁹

Future Directions

Today's existing technologies including fluoroscopy, intracardiac echocardiography, and electroanatomical mapping systems cannot evaluate for the presence of transmural ablation lesions in real time during catheter ablation of AF. This frequently leads to the development of lesion gaps, the main cause of AF recurrence. Researchers are developing techniques for real-time MRI catheter navigation as well as thermography and lesion assessment.^{40–42} This would provide real-time guidance and direct feedback during AF ablation procedures and holds the promise of delivering a personalized strategy to patients while improving the safety and efficacy of catheter ablation of AF.

Study Limitations

First, the vast majority of studies on LGE-MRI of atrial scarring have come from a few leading centers. And currently there is no standard for the LGE-MRI acquisition, image processing, and signal-intensity thresholds used to define healthy vs scarred myocardium. Second, the cardiac MRI ablation system has been introduced in a few specialized centers and showed feasibility and safety of MRI-compatible catheters that can be navigated under 3-Tesla MRI guidance, delivering a radiofrequency pulse and allowing real-time acute tissue edema and injury visualization. Whether these techniques can be reproduced in other centers and used in clinical practice has not been determined. Third, imaging expenditures for AF ablation vary substantially by the imaging strategy chosen, with higher costs for electroanatomic mapping + CT/MRI + TEE. Lately the US health care system has been moving toward a more cost-conscious environment. Cardiac CT/MRI and TEE are not part of the AF ablation billing code, but as of January 1, 2013, electroanatomic mapping and ICE are included in the AF ablation billing code.⁴³ Fourth, contraindications such as end-stage renal disease, abandoned pacemaker/defibrillator leads, and severe claustrophobia represent standard contraindications for MRI.

Conclusion

The need to improve catheter ablation of AF has provided exciting new imaging modalities. Cardiac MRI has become

an indispensable imaging tool to personalize the AF ablation strategy, assess the efficacy and potential complications of AF ablation, and guide repeat ablation. However, it also underlines the considerable technical challenges still to be faced to achieve accurate and standardized cardiac MRI characterization of atrial scarring.

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