

Magnetic Resonance Imaging: Description of Technology and Protocols

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Abstract

Since its introduction in the late 1970s, catheter-based radiofrequency ablation has evolved from a primitive and experimental procedure to the mainstay for arrhythmia management it is today. Initial intracardiac catheter navigation was fluoroscopy based, and therefore subject to x-ray limitations and side effects. However, accurate catheter location within the cardiac chambers has required electrophysiologic confirmation of catheter positioning. This led to the development of conventional cardiac mapping techniques. The limitations of fluoroscopy and conventional mapping techniques led to the development of electro-anatomical mapping systems (EAM), in which information regarding catheter position in a 3D space is combined with electrophysiological information in real time to provide an accurate localization of the catheter tip while, at the same time, data regarding electrophysiological properties of the underlying myocardial substrate. Eventually, the mechanisms of more complex arrhythmias, such as atrial fibrillation and scar-based monomorphic ventricular tachycardia, started to be elucidated. This was followed by more difficult ablation procedures that required more accurate mapping systems able to provide real-time information. The introduction of EAM combined with Cardiac Computerized Tomography (CCT), cardiac Magnetic Resonance Imaging (cMRI), and real-time intracardiac echocardiography (ICE) allows for more precise mapping with significant improvement in cure rates for ablation procedures. However, most of these techniques are essentially x-ray based and expose the patient and the operator to the noxious effects of ionizing radiation.

Keywords

Catheter-based radiofrequency ablation • Electro-anatomical mapping systems • Cardiac Computerized Tomography • Cardiac Magnetic Resonance Imaging • Intracardiac echocardiography

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limitations and side effects. However, accurate catheter location within the cardiac chambers has required electrophysiologic confirmation of catheter positioning. This led to the development of conventional cardiac mapping techniques. Initial and current conventional electrophysiologic mapping techniques rely on astute observations and maneuvers to uncover the arrhythmia anatomic substrate and pathophysiologic mechanisms. However, as progress was made in the understanding of the mechanisms underlying arrhythmias, the limitations of fluoroscopy and conventional mapping techniques became apparent.

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2.1 MRI for Arrhythmic Substrate Evaluation: Tissue Characterization and Anatomic Considerations

2.1.1 Atrial Fibrillation Ablation

2.1.1.1 Anatomical Considerations

Atrial fibrillation (AF) is the most common sustained cardiac arrhythmia, affecting more than two million people in the United States,² with an incidence rate of 0.4%³ of the general population. Electrical pulmonary vein isolation (PVI) using radiofrequency (RF) ablation is effective in symptomatic, drug-refractory AF. Still, reported success rates of the procedure vary significantly with reported AF recurrences ranging from 25% to 60%.

Ever since it was first published in 1998 by Haissaguerre et al., pulmonary vein (PV) triggers have been recognized as the most common source of paroxysmal atrial fibrillation; electrical isolation of the PV has remained the cornerstone of atrial fibrillation ablation.⁴ Most ablation techniques include, in one way or the other, a group of lesions distributed in a circular fashion to electrically isolate the PV so that it becomes of utmost importance then to clearly define the left atrial (LA) and PV anatomy prior to any ablation.

PV anatomy is variable in the general population, and this is more significant in the AF patient population. Kato et al.⁵ observed up to 38% anatomical variants in patients with AF, these patients typically had larger PV diameter than controls. Wazni et al.³ confirmed the presence of a right middle PV in 18–29% of patients undergoing evaluation for AF ablation,

and this structure has been described as a focus for AF initiation. The importance of a clear understanding of the patient's anatomy is of paramount importance when planning an ablation procedure. cMRI can very clearly demonstrate the presence, location, and anatomical variants of PV's prior to ablation; allowing for procedural planning.

2.1.1.2 Integration Between Left Atrium cMRI and Non-fluoroscopy Based Mapping Systems

Integration of LA cMRI images with a non-fluoroscopy-based mapping system is a crucial step in AF ablation, since it allows for precise catheter monitoring in a real-time three-dimensional manner during ablation. Integration typically consists in fusing two images: CCT or cMRI with an electro-anatomical map (EAM) or shell of the LA. This process usually consists of three steps: (1) image acquisition, (2) segmentation, and (3) registration. Accuracy of integration is crucial for safe catheter navigation and positioning; however, pitfalls related to integration of CCT/cMRI with EAM systems could occur due to registration errors and changes in the LA volume, size, and shape between the time of image acquisition and integration with the EAM system.

2.1.1.3 Tissue Characterization, Staging of Atrial Fibrillation, and Prediction of AF Ablation Success

Late gadolinium enhancement-MRI (LGE-MRI) of the LA has been used as a marker for LA fibrosis and structural remodeling. Oakes et al.⁶ have shown that the amount of LGE in the LA is a powerful predictor of AF ablation outcome. The rate of AF recurrence post-ablation was directly related to the degree of LA LGE pre-ablation.⁶ The amount of LGE of the LA as a marker of scar formation post-AF ablation has also been directly correlated with ablation success in a pilot study.⁷

The use of LGE-MRI pre-ablation for risk stratification and ablation success prediction has allowed for the development of a personalized management approach to atrial fibrillation. Upon initial clinical evaluation and after determining the AF burden, a cardiac MRI was acquired. The following image acquisition parameters are used.

2.1.1.4 MRI Image Acquisition

Pre-ablation cardiac MRI is obtained either on a 1.5 T Avanto or on a 3.0 T Veerio scanners (Siemens Medical Solutions, Erlangen, Germany) using a TIM phased-array receiver coil. The scan is acquired 15 min after 0.1 mmol/kg Multihance (Bracco Diagnostic Inc., Princeton, NJ) contrast agent injection, using a 3D inversion recovery, respiration-navigated, ECG-gated, and gradient-echo pulse sequence. Typical acquisition parameters were free-breathing using navigator gating, a transverse imaging volume with voxel size = 1.25 × 1.25 × 2.5 mm, and GRAPPA with $R=2$ and 46 reference

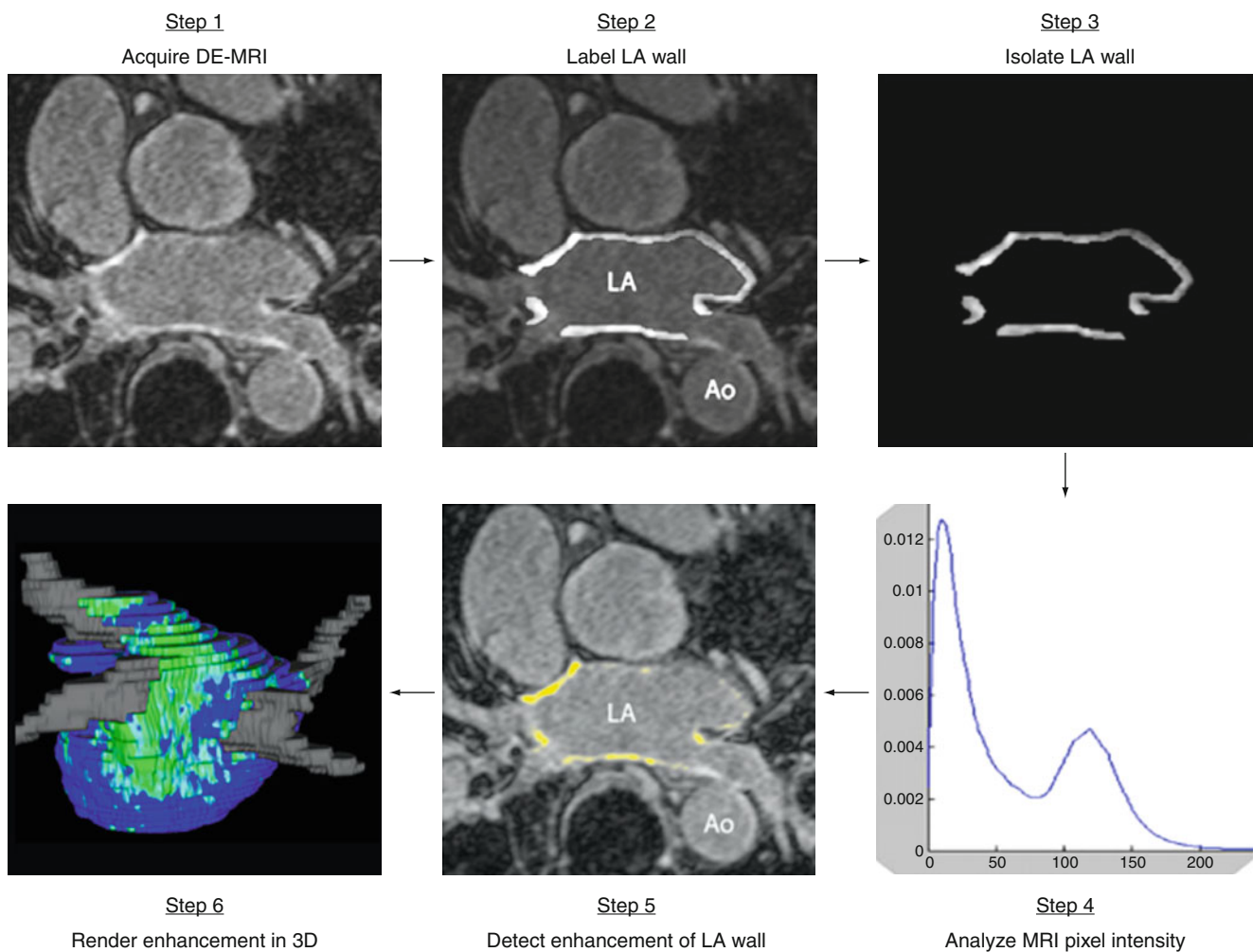


Fig. 2.1 LGE-MRI quantification of pre-ablation fibrosis/structural remodeling and postablation scarring. After LGE-MR images are obtained (1), the endocardial and epicardial borders are manually contoured and isolated (2, 3), and the extent of LGE is then quantified using a pixel intensity distribution (4), qualitative confirmation is then

performed, a color lookup table mask is then applied to differentiate enhanced and non-enhanced tissue (5), and finally a 3D rendering of the LA is generated allowing for better visualization and spatial localization of the late gadolinium enhancement (6)

lines. ECG gating is used to acquire a small subset of phase encoding views during the diastolic phase of the LA cardiac cycle. The time interval between the R-peak of the ECG and the start of data acquisition was defined using the cine images of the LA. Fat saturation is used. The TE of the scan (2.3 ms) is chosen such that fat and water are out of phase and the signal intensity of partial volume fat-tissue voxels was reduced allowing improved delineation of the LA wall boundary. The T1 value for the LGE-MRI scan is identified using a scout scan. Typical scan time for the LGE-MRI study is 5–10 min.

2.1.1.5 LGE-MRI Quantification of Pre-ablation Fibrosis/Structural Remodeling and Post Ablation Scarring

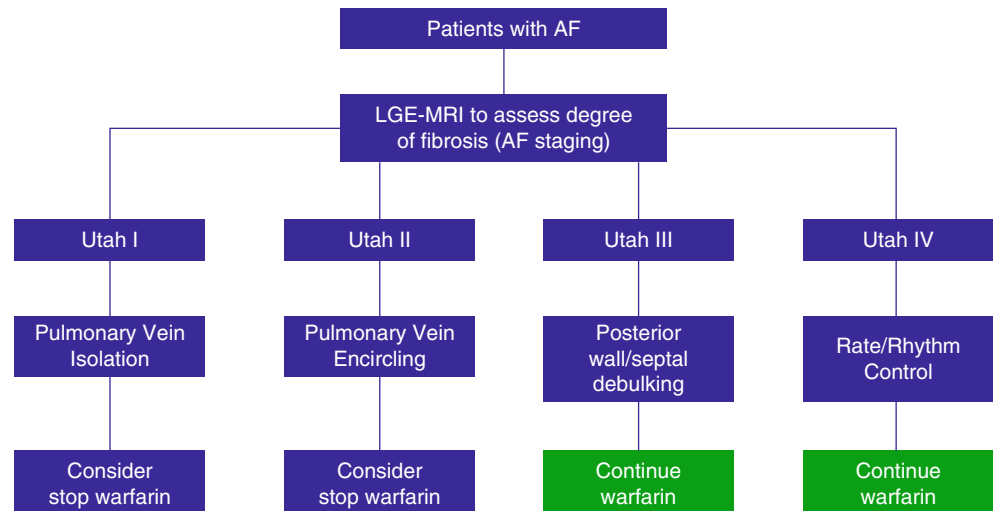
After image acquisition, the epicardial and endocardial LA borders are manually contoured using the CoreView image

display and analysis software. The relative extent of pre-ablation enhancement and post-ablation scar is then quantified within the LA wall with a threshold-based algorithm utilizing pixel intensities from normal based on a bimodal distribution (Fig. 2.1). Since post-ablation scar pixel intensity is significantly higher than pre-ablation delayed enhancement, a different threshold is used for analysis and imaging of scar.

2.1.1.6 Staging AF Using MRI

Supported by outcome data we have established at the University of Utah, a clinical staging system composed of four stages based on the amount of pre-ablation delayed enhancement (fibrosis) as a percentage of the volume of the left atrial wall.⁸ This clinical staging system includes four stages: Utah I $\leq 5\%$ enhancement, Utah II $>5\text{--}20\%$, Utah III $>20\text{--}35\%$, and Utah IV $>35\%$. When performing a

Fig. 2.2 University of Utah proposed LGE-MRI-based management algorithm for patients with AF



multivariate analysis, it was found that the number of PV isolated in patients with Utah stage II and the total amount of scar in those with Utah stage III were predictors of success. Patients with minimal pre-ablation fibrosis, Utah stage I, did well regardless of the number of PV isolated or the total amount of scar, whereas those with advanced atrial remodeling as assessed by LGE-MRI, Utah stage IV, did poorly regardless.⁸

Moreover, in a multivariate regression model, LGE-MRI evaluation of the left atrial substrate was shown to improve the predictive value of the CHADS₂ score, allowing defining patients at higher risk of stroke despite having a low or moderate CHADS₂ score.⁹ Patients with a previous stroke had a significantly higher percentage of LA fibrosis compared to those without ($24.4\% \pm 12.4$ vs. $16.1\% \pm 9.8$, $p < 0.001$). There was also a significant difference in the rate of thromboembolism between patients with Utah stage I and those with stage IV. Also it was found that patients with higher risk for stroke (CHADS₂ score ≥ 2) had higher amounts of LA fibrosis. Using univariate and multivariate regression analysis, LGE-MRI quantified left atrial structural remodeling was independently associated with stroke.⁹ Based on this staging system, a comprehensive cMRI-based AF management algorithm (Fig. 2.2) has been developed, which helps in triaging patients to AF ablation, as well as planning a corresponding ablation strategy and future anticoagulation strategy.

2.1.2 Safety

Control of collateral damage is critical during AF ablation. The LA is anatomically related with several vital structures; the pulmonary artery runs along the LA dome, the ascending

aorta relates with the LA anterior wall and dome, the descending aorta with the posterior wall, the phrenic nerve is anterior to the right pulmonary veins, and the esophagus runs behind the posterior wall and the left inferior PV. Understanding of these relationships and monitoring of these anatomical structures during ablation is of paramount importance to avoid disastrous complications. LGE of the esophagus has been used to monitor for post-ablation injury.¹⁰ In one report, Badger et al.¹¹ studied 41 patients' LGE-MRI pre-AF ablation, 24 h post-AF ablation, and 3 months after the ablation. Five patients demonstrated esophageal enhancement 24 h post-ablation and esophageal injury confirmed by esophagogastroduodenoscopy (EGD). EGD and cMRI were repeated a week later and confirmed resolution of esophageal LGE and endoscopic resolution of these lesions as well. Follow-up cMRI at 3 months post ablation demonstrated no LGE on the esophageal wall (Fig. 2.3).

2.2 Ventricular Tachycardia Ablation

Arrhythmia substrate evaluation is critical for ventricular tachycardia (VT) evaluation and ablation strategy planning. cMRI has the capacity to assess not only ventricular systolic function but also, and simultaneously, to provide insights into the myocardial underlying pathology.

2.2.1 Scar-Based Monomorphic Ventricular Tachycardia: Ischemic VT

VT associated with myocardial scars, either ischemic (Fig. 2.4a–c), due to sarcoidosis, or cardiomyopathy, is

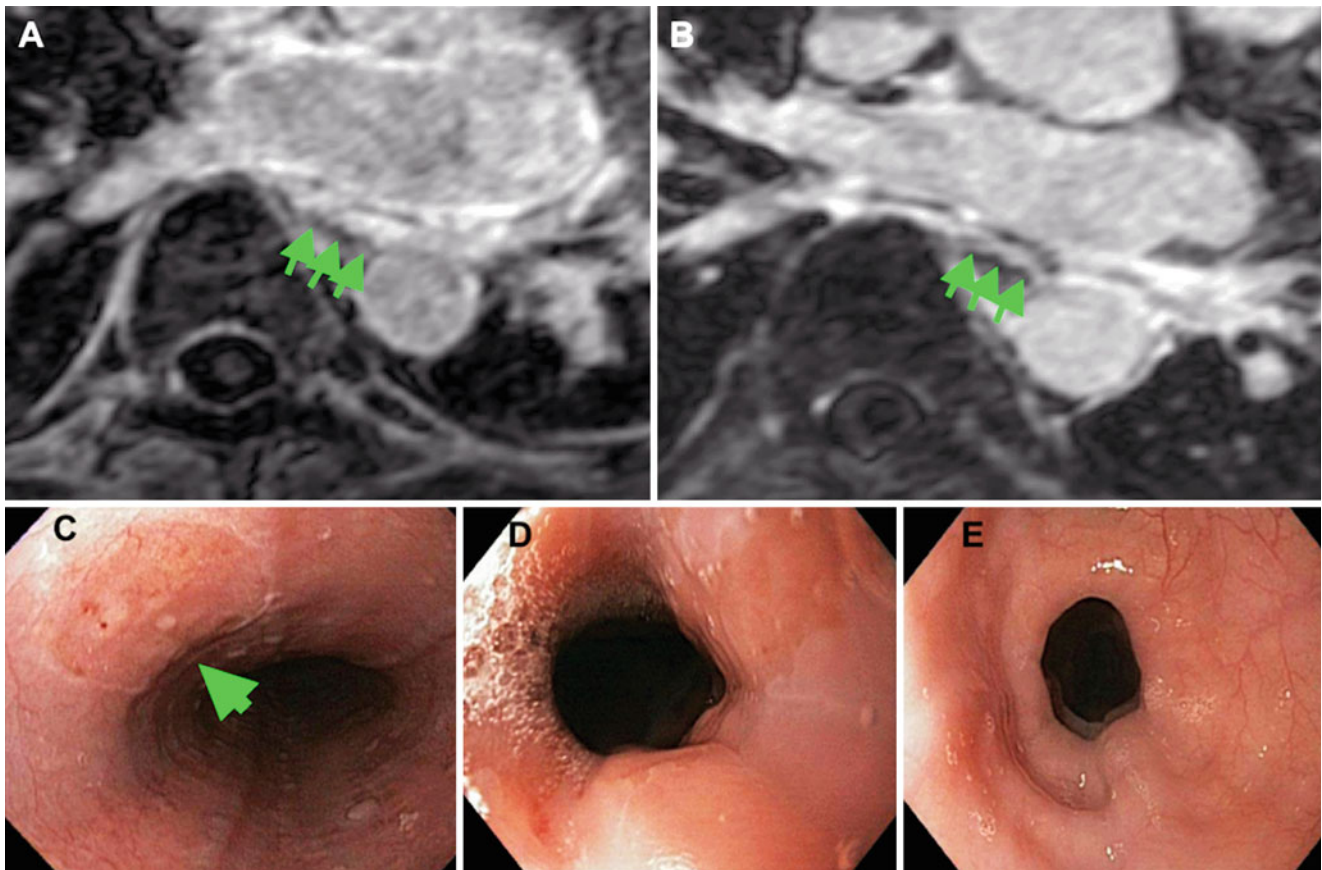


Fig. 2.3 LGE-MRI of the esophagus and EGD. (a) LGE-MRI demonstrates enhancement of the anterior esophageal wall (arrows) which correlates with a lesion (green arrow) found on EGD (c). (b) A week

later, there has been resolution of late gadolinium enhancement on MRI (arrows) and resolution of the lesion on EGD (d and e)

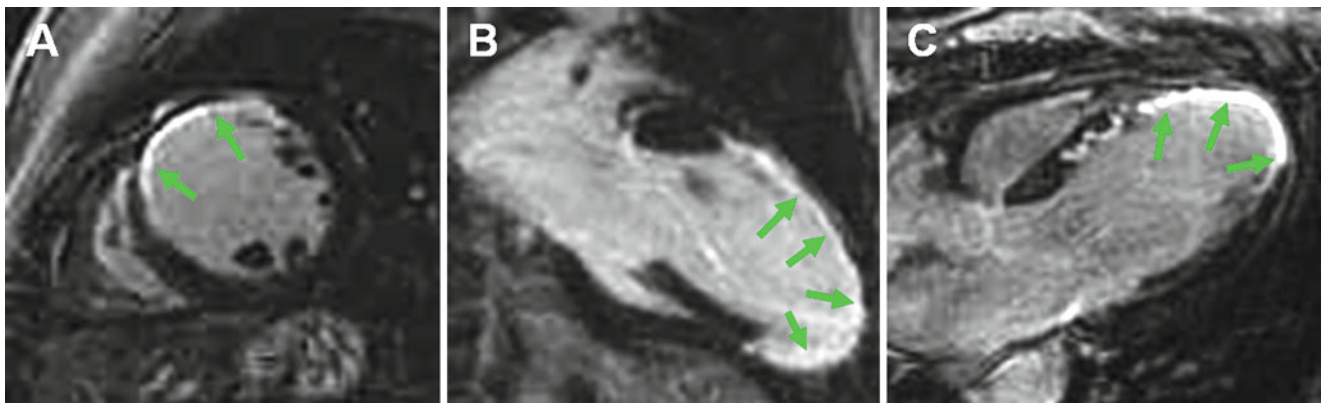


Fig. 2.4 Characteristic cMRI of patients with ischemic scar. Cardiac LGE-MRI (late gadolinium enhancement phase sensitive inversion recovery (PSIR) sequence) of patient with ischemic cardiomyopathy and

scar-based monomorphic ventricular tachycardia (a: short axis view, b: two chamber view, and c: long axis view) demonstrating a scar (green arrowheads) in the distal antero-septal segments of the LV (bright area)

typically a monomorphic re-entrant arrhythmia dependent upon the presence of a conduction isthmus. This isthmus could be inside the scar, around the scar, or around a fixed anatomical structure (i.e., cardiac valves). These arrhythmias are usually not well tolerated hemodynamically.

Different strategies for the mapping of these VTs include scar/substrate assessment with electro-anatomical mapping system, pace mapping, and evaluation of diastolic potentials. These different strategies, however, are time consuming, adding length and risk to these procedures.

LGE-MRI provides a reliable assessment of myocardial scar, particularly in ischemic substrates. Bello et al. found, in 18 patients, a correlation between infarct surface area and infarct mass as defined by LGE-MRI and VT inducibility on EPS.¹² On another larger study, Schmidt et al. demonstrated the association between “scar border zone,” a distinct zone than dense scar based on pixel intensity on LGE-MRI, and inducibility in EPS.¹³ In this study, the amount of scar border zone was a good predictor of inducibility, whereas the total amount of dense scar was not. Information about VT substrate has been used, albeit experimentally, to predict the VT circuit. Ashikaga et al. correlated, in an animal model, surface ventricular mapping with ex-vivo high-resolution cMRI and found correlation between exit sites and conduction isthmus with isles of viable myocardium within the scar.¹⁴

2.2.2 Arrhythmogenic Right Ventricular Dysplasia/Cardiomyopathy

Arrhythmogenic right ventricular dysplasia/cardiomyopathy (ARVD/C) is cardiomyopathy which affects mainly the right ventricle (RV). It is characterized by fatty/fibro-fatty replacement and myocyte loss, ventricular aneurysms, ventricular arrhythmias, and right ventricular failure. There is mounting evidence that the underlying etiology of ARVD/C is desmosomal dysfunction.¹⁵ Its prevalence is estimated to be around 1:5,000 in the United States, and accounts for 5% of all sudden cardiac death in patients younger than 35 years old in the United States. Its diagnosis is based on a set of major and minor criteria established by the Task Force of Cardiomyopathy.¹⁶ They include evaluation for structural and electrophysiological abnormalities, as well as elements from the patient history.

Cardiac MRI is a very useful noninvasive tool for the evaluation of ARVD/C since it can define the presence of myocardial fat infiltration, observed in T1-weighted sequences,¹⁵ and it can also allow for evaluation of the structure of the RV and quantification of its function.

2.2.3 Ventricular Tachycardia in Structurally Normal Ventricles (Idiopathic Ventricular Tachycardia)

Approximately 10% of all ventricular tachycardias occur in ventricles that are structurally normal.¹⁷ The presence of sub-clinical structural abnormalities is not always evident in the echocardiogram and/or coronary angiogram which are usually normal. MRI in these cases may assist in the differential diagnosis and point toward a different etiology.

2.3 Radiofrequency Ablation Lesion Characterization

Characterization of the myocardial changes following RF ablation is of importance since it would allow for validation of therapy delivered and ultimately for ablation endpoints.

2.3.1 Acute Wall Edema Post Ablation

Acute edema, enhancement on T2w images performed immediately after AF ablation, correlates significantly with low voltage areas (defined as <0.05 mV) mapped using the CARTO system. However, the area enhanced with T2w imaging is much larger than the area covered by LGE on MRI acutely post-AF ablation.¹⁸ Acute post-ablation edema is seen not only in regions directly subjected to RF energy but also in distant regions (Fig. 2.5) and it does not predict final scar formation defined by LGE-MRI at 3 months.¹⁸ A LGE-MRI at 3 months after AF ablation shows loss of enhancement on T2w images consistent with edema resolution in areas free of scar. Edema seen acutely in regions other than in ablated areas suggests a mechanism other than direct radiofrequency thermal lesion as its cause.

Finally, the presence of edema in regions away from areas that result in scar formation, as well as its association with low voltage on electro-anatomical mapping may explain, at least partially, the presence of acute PV disconnection, and late reconnection with edema resolution, or ventricular myocardial recovery following VT ablation.¹⁸

2.3.2 Late Gadolinium-Enhanced Defined Scar and Non-reflow Phenomenon

Heterogeneity in the LA wall is seen on acute post-ablation LGE-MRI scans with portions showing very little or no enhancement at all even in areas that received direct RF energy (Fig. 2.6). In a porcine model of ablation, these areas correlated well with lesion formation, particularly with areas with the highest amount of injury. Within minutes there is resolution of these areas of non-enhancement and they manifest all the features of ablated/scarred areas. These areas of no-enhancement are believed to correspond to areas of no-reflow, phenomenon similar to that seen in ventricles in the immediate post-MI period.¹⁸

2.3.3 Late Imaging and Recurrences

The amount of scar and the number of circumferentially scarred PVA on LGE-MRI is associated with better outcomes

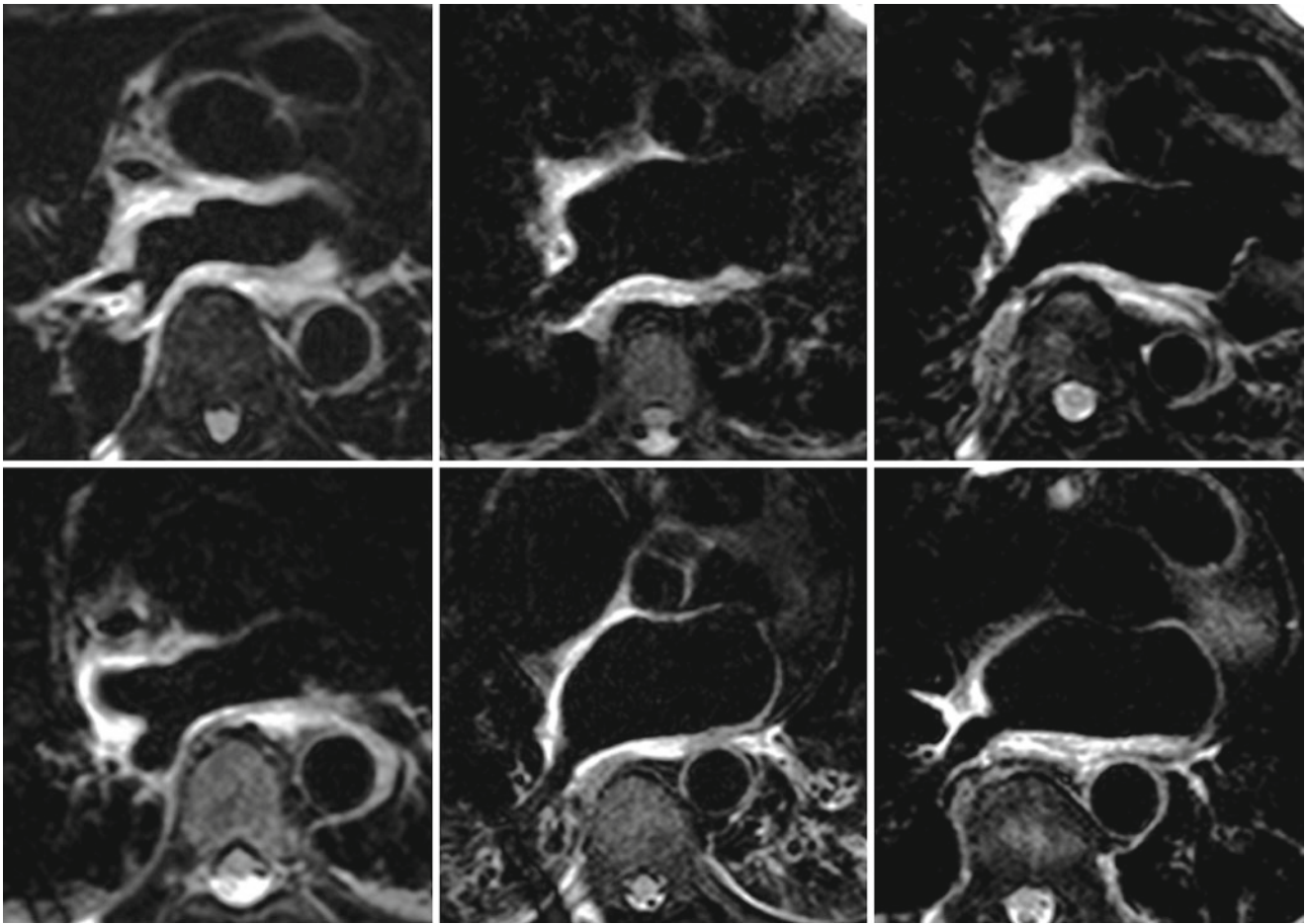


Fig. 2.5 *Post-ablation edema extends beyond ablated regions.* Cardiac MRI from six patients post-AF ablation demonstrates edema (bright T2w signal) extending not only in regions where RF energy was

delivered (posterior wall and PV antrum) but also remote LA regions (anterior wall/dome and lateral wall)

for AF ablation, confirming earlier studies that total LA ablation scar burden is associated with AF termination.¹⁹ However, complete PVA isolation is difficult to achieve and complicated by the fact that certain changes seen acutely are reversible over a 3-month period.

Acutely post-ablation voltage and LGE-MRI defined scar do not have a good correlation. However, acute LGE-MRI areas correlate well with areas of low voltage at 3 months. These areas of acute LGE-MRI likely represent areas with irreversible damage from RF ablation whereas the larger area of low voltage during the acute post-ablation period likely represents a combination of tissue edema, other reversible changes, and areas that will scar completely.

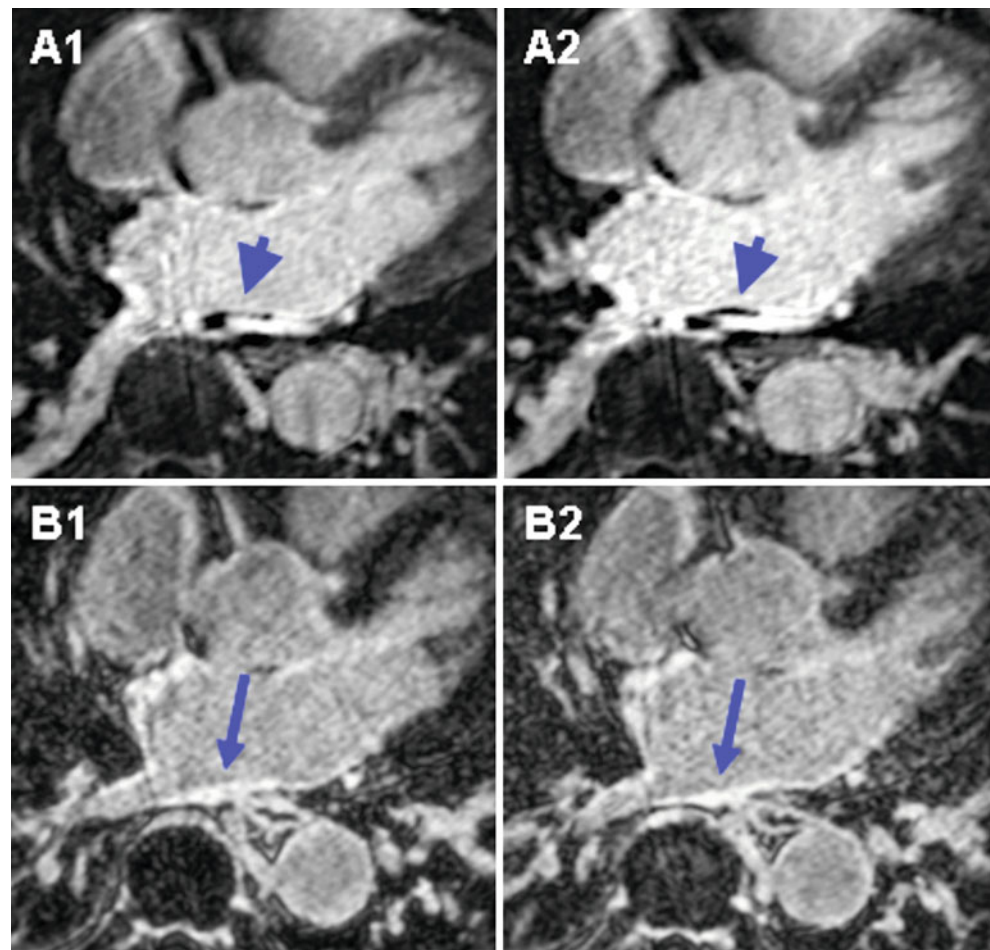
LGE-MRI can also accurately identify the location of breaks in ablation lesion sets, and its correlation with conduction recovery, which may explain post-ablation AF recurrences.¹⁹ Badger et al.²⁰ demonstrated that AF recurrences following ablation are associated with significant gaps

between lesions, and that these gaps correlated well with recovery of local EGMs or PV electrical conduction. This has allowed to better plan and tailor re-do procedures for patients with PV tachycardias, atrial/flutter, or atrial fibrillation.

2.4 The Future: Real-Time-MRI

The assessment of lesion formation during electrophysiologic procedures has always been a challenge; cMRI allows for visualization of location and extent of RF ablation lesion, scar formation in the myocardium, and potentially real-time assessment of lesion formation. Real-time MRI (RT-MRI)-based imaging and ablation system has the potential advantage of tissue lesion visualization during RF delivery, which could be used as an ablation end point. Electrophysiology RT-MRI-guided procedures have been carried out by a few laboratories.

Fig. 2.6 *Non-reflow phenomenon on LGE-MRI.* (a1, a2) Cardiac LGE-MRI of two patients immediately following AF ablation demonstrates areas of LGE mixed with areas of no enhancement in the posterior wall (blue arrowheads). These same patients underwent LGE-MRI at 3 months post ablation. (b1, b2) The above areas correlated well with scar formation in the posterior wall (blue arrows)



MRI-guided ablation in the atrium has recently been reported by Schmidt et al.²¹ and by Hoffmann et al.²² In one of these studies, MRI angiography of the atrium was acquired, the atrium surface was segmented, and real-time catheter navigation was then carried out using this 3D reconstruction; however, no images were acquired during ablation²¹; rather, immediately postablation lesion formation was confirmed by LGE imaging. In the other study,²² the catheters were navigated using RT-MRI sequences; however, there was no immediate tissue visualization during RF delivery and lesion formation, although there was T2w evaluation of the ablation site just before and after the ablation of the cavo-tricuspid isthmus. These two studies were done in 1.5-T MRI.

At our EP-MRI suite, we could demonstrate the feasibility to safely navigate and pace and record intracardiac EGMs in the atrial chambers under 3-T real-time MRI guidance.²³

We used a novel 3-T real-time (RT) MRI-based porcine RF ablation model with visualization of lesion formation in the atrium during RF energy delivery (Fig. 2.7).

In this model, RF energy was delivered under cMRI visualization at 3-T using custom RT-MRI software. A novel MRI-compatible mapping and ablation catheter was also used. Under RT-MRI, this catheter was guided and positioned within either the left or right atrium. Unipolar and bipolar electrograms were recorded. The catheter tip-tissue interface was then visualized with a T1w FLASH (T1-weighted fast low angle shot) sequence. RF energy was then delivered in a power-controlled fashion, and myocardial changes and lesion formation were visualized with a T2w HASTE (half Fourier with single shot turbo spin echo) sequence during the ablation. The presence of a lesion was confirmed by LGE-MRI and macroscopic tissue examination.

According to these studies, MRI-compatible catheters can be navigated and RF energy safely delivered under 1.5- and 3-T RT-MRI guidance. It was also feasible to record EGMs in the atrium and ventricle during real-time image acquisition. Real-time visualization of lesion as it forms during

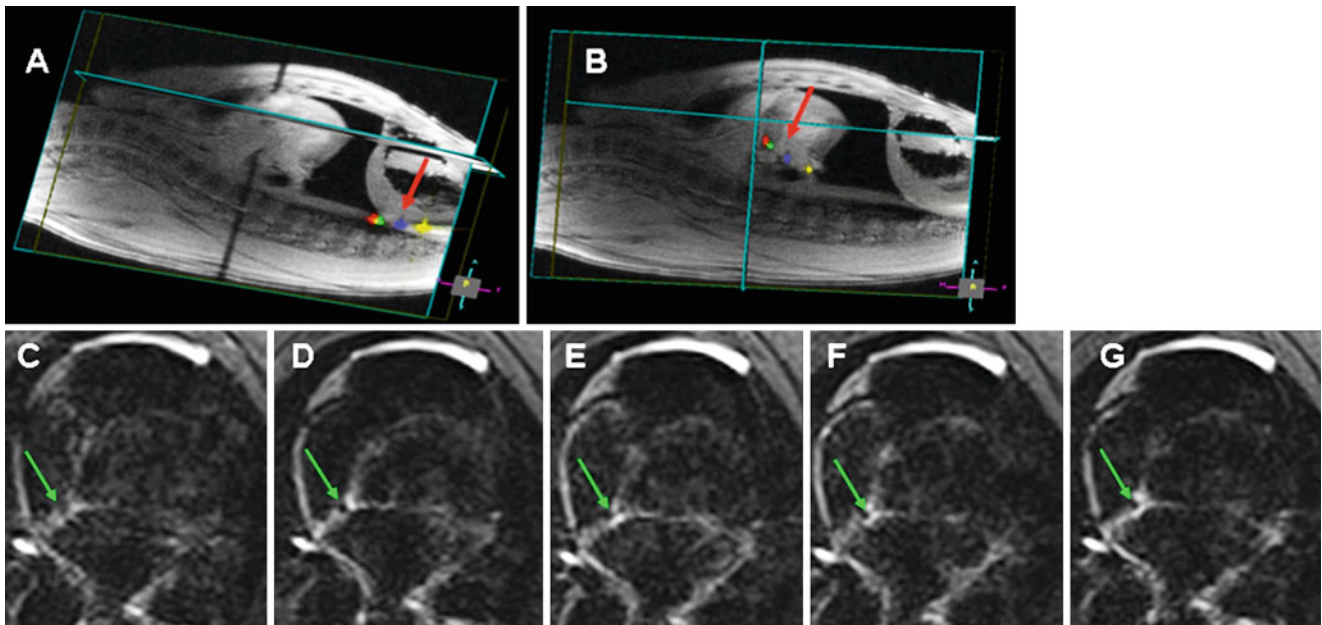


Fig. 2.7 Real-time MRI ablation and lesion visualization at 3-T. (a and b) MRI-compatible RF catheter guided under RT-MRI from the IVC into RA, the signal from the tracking elements is displayed and color coded (red: distal and yellow: proximal) to allow the operator

catheter visualization. (c–g) Real-time 20 W power lesion can be seen (T2w HASTE) as it is being formed from catheter touch down (c) to 45 (g) (green arrows)

delivery of RF energy was possible and demonstrated using T2-w HASTE imaging under 3-T.

Finally, catheter visualization and myocardial tissue imaging under RT-MRI during RF energy could help improve ablation procedure outcomes by immediate assessment of ablation endpoints in the myocardium.

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