Atrial fibrillation (AF) is a frequently encountered cardiac arrhythmia that is an independent predictor of increased mortality and morbidity amongst those who suffer from the disease [1]. Affecting nearly 1.0–1.5% of the population, the incidence of AF is predicted to increase from its current 2.3 million to 10 million people by 2050 [2]. The complex nature of the disease and the projected increase in prevalence will undoubtedly place a significant strain on healthcare systems and practicing physicians around the world. For these reasons, finding better and more cost-efficient treatment options for patients suffering from this arrhythmia is of the utmost importance.

Atrial fibrillation has a complex etiology and treatment success rates with medical therapy alone are less than ideal and carry significant risks [3,4]. This has caused many researchers in this field to focus their attention on finding interventional treatment options to potentially cure this arrhythmia. In 1998, Hassiguere et al. made a landmark breakthrough when they described ectopic foci in the pulmonary veins, which appeared partly responsible for initiating AF circuits [5]. This discovery led to the development of catheter-based ablation aimed at electrically isolating these triggers from the left atrial (LA) substrate. Initial ablation techniques targeted any regions of the pulmonary vein (PV) ostial demonstrating electrical activity. [6–8] This approach was later modified to include wide, encircling lesions at distinct anatomical landmarks in an attempt to disrupt LA–PV conduction pathways [9–11]. Although these techniques, as well as others, have been heavily studied and modified to increase procedural success, they continue to produce less than ideal success rates, particularly amongst certain subgroups of AF patients [6,12].

As ablation technique has evolved over the past decade, there has been a greater emphasis placed on investigating new methods that can assist in the ablation procedure and improve the knowledge regarding the underlying mechanisms responsible for AF initiation and maintenance. A recent advancement has been the implementation of a novel MRI sequence that depicts the location and intensity of radiofrequency-induced scar in the LA following AF ablation [13,14]. This scan sequence enables physicians and researchers to locate ablation-induced scar in relation to the pulmonary veins and other anatomical structures of interest [14]. This new technology offers many potential uses and benefits to help aid physicians who practice catheter ablation of AF.

In this review, we will describe this novel MRI scan sequence and its emerging role in the interventional treatment of AF. We will primarily focus on how MRI is being used to evaluate postprocedure scar lesions and new ablative techniques. We will also discuss how delayed-enhancement cardiovascular MRI (DE-MRI) holds the potential to aid in the selection of appropriate candidates for ablation procedures and to provide greater understanding of the underlying mechanisms of this cardiac arrhythmia.

**Delayed-enhancement MRI & the visualization of ablation scar**

Delayed-enhancement cardiovascular MRI is an established method for visualizing numerous cardiac pathologies, including myocardial necrosis and inflammation [15–18]. The mechanism of this scan sequence is based on the poor washout kinetics of the contrast agent gadolinium in nonviable tissue [15]. DE-MRI has previously been used to describe diseases in the left ventricle (LV), where the thick myocardial wall facilitates the visualization of washout kinetics between healthy myocardium and diseased tissue [15,19]. Although DE-MRI is an effective
modality to describe and quantify LV diseases, implementation of this technology to diseases of the atria has been difficult. This is mainly owing to the thin nature of the LA wall, which does not allow for the easy visualization of contrast patterns. However, recent advancements in spatial and temporal resolution of cardiac MRI have resulted in images that clearly depict this cardiac chamber, resulting in the ability of electrophysiologists to visualize the LA tissue response following AF ablation (Figure 1) [13,14].

This new scan sequence, implemented at our institution, is acquired on a 1.5 Tesla Avanto clinical scanner (Siemens Medical Solutions, Erlangen, Germany) using a total imaging matrix phased-array receiver coil. DE-MRI is acquired approximately 15 min after gadolinium injection using a 3D inversion recovery, respiration navigated, ECG-gated, gradient echo pulse sequence. Typical acquisition parameters include free-breathing using navigator gating, a transverse imaging volume with voxel size = 1.25 x 1.25 x 2.5 mm (reconstructed to 0.625 x 0.625 x 1.25 mm), TR/TE = 6.3/2.3 ms, inversion time (TI) = 230–270 ms, GRAPPA with R = 2 and 32 reference lines. Typical scan time for the DE-MRI study ranges between 5 and 10 min depending on subject respiration and heart rate [14].

Detection of postablation scar can then be quantified postablation using a semiautomated computer algorithm. This is based on the distribution of pixel intensities between normal LA wall tissue and radiofrequency-induced scarring [14]. Generation of 3D MRI models can then be created using custom software in order to display the location and size of scar patterns in relationship to anatomical landmarks such as the pulmonary vein antra (PVA). These LA segmentatons can be used to evaluate whether intraprocedural end points for PV antral isolation are met postablation, such as whether encircling PV lesions are complete and continuous (Figure 2) [14]. This data has the potential to provide significant insight into the efficacy pathophysiology of ablation procedures. For example, these models can be used to retrospectively analyze how different scar patterns correlate with clinical outcome, such as the relationship between complete PVA anatomical block with procedure success, as well as the role of additional ablation techniques on procedure outcome [20]. This could potentially provide additional insight into which ablation strategies are most conducive to AF termination in different subgroups of AF patients [20].

Using DE-MRI to assist in AF ablation
Pulmonary vein antrum isolation is an ablation strategy that targets complete PV isolation by creating continuous and encircling scar lesions at the LA–PV junction. It is speculated that anatomical gaps within the linear ablation lines and inability to achieve complete transmural lesions may be partially responsible for the inability to achieve complete electrical block. Recurrence...
of electrical conduction between the PV and LA substrate has been shown to be a significant contributor to procedure failure [21-23].

The ability of DE-MRI to identify breaks in linear ablation lesions allows physicians to know the exact location of the anatomical regions that lack adequate scar formation. Using a step-wise ablation approach, these unscarred regions and correlation with return of electrical potential can be targeted during repeat procedure; therefore, increasing the likelihood of achieving complete PV antral scarring [24]. At our institution, we have employed this multistep approach for those electing to undergo repeat ablation. In these cases, patients undergo DE-MRI following their failed procedure in order to evaluate scar lesions. 3D segmentation of the LA is performed with arrows attached to regions of unscarred antra. This map is then used prior to the procedure to analyze the anatomical regions requiring additional ablation. These regions are then confirmed with return of electrical potentials and targeted during repeat procedure. Figure 3 demonstrates an example of this approach. In this example, two patients show incomplete PV antral scarring (top row) following the failed ablation procedure. The regions of unscarred antrum were targeted with arrows prior to the repeat procedure. During the second procedure, these regions were reablated resulting in completion of scar lesions as confirmed with follow-up MRI.

Identification of gap lesions using DE-MRI offers many other potential benefits in the treatment of AF. Earlier studies have demonstrated that a significant amount of patients experience new onset atrial arrhythmias, such as atrial tachycardia and/or atrial flutter,

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Figure 2. Generation of 3D models of the left atrium demonstrate the relationship of ablation scar to anatomical structures. In this example, scar can be seen around the left common ostia and both the right inferior and superior pulmonary veins. Also, scar burden can be detected postablation in regions of the posterior wall.
following AF ablation [25–27]. Evidence shows that these arrhythmias often occur from conduction gaps in linear ablation lines, forming a proarrhythmogenic substrate suitable for macro-re-entrant tachyarrhythmias. Closing these conduction gaps during repeat ablation has been demonstrated to eliminate these arrhythmias [28]. With the ability of DE-MRI to accurately visualize breaks in ablation lines, this technology might be used to assist the electrophysiologist in understanding the relationship between postablation tachyarrhythmia and scar lesions. Closure of the gaps responsible for the arrhythmia could be confirmed by repeat imaging following the procedure using this scan sequence.

Postablation MRI analysis: understanding new ablation strategies

There is substantial evidence that the mechanisms of AF are multifactorial [29]. Although it is clear that a prevalent source of the arrhythmia originates from the PVs, research clearly indicates many other factors responsible for both AF initiation and maintenance [30–34]. Owing to the lack of understanding regarding the precise mechanisms responsible for AF in different patients, some have speculated whether an individually tailored ablative strategy would be more beneficial than a standardized approach [35]. However, this patient-specific approach requires a more thorough understanding regarding which mechanisms might be responsible for the initiation and maintenance of the arrhythmia in different subgroups of patients. In order to address this issue, we speculate that postablation DE-MRI has the potential to reveal a better understanding regarding the scar characteristics associated with the best clinical outcome in selected AF patients. For example, scar data from postablation MRI might be used to test the current hypothesis that paroxysmal AF patients stand to benefit more from PV antrum isolation as compared with persistent AF patients. This information might provide practitioners with an idea of which ablation technique is most appropriate in different AF patients.

Delayed enhancement cardiovascular MRI is currently being used to investigate the safety and efficacy of new ablation approaches. For example, various ablation techniques have been adapted to address the role of the posterior wall in the chronic fibrillatory process [36]. Substrate modification relies on decreasing the amount of viable LA tissue capable of harboring AF by ablating significant portions of the posterior wall. This can be achieved by wide encircling ablation or by left atrial debulking [37]. Pappone et al. have speculated that the extent of left atrial ablation (>30%) is a more important prognostic indicator for procedure success than PV isolation [9]. This finding is consistent with recent reports describing total LA scar burden as a significant predictor of AF termination [14,39]. Prior to the implementation of DE-MRI, quantification of LA scar could only be estimated by invasive techniques. However, using a threshold-based algorithm that measures the pixel intensity.
distribution between normal LA tissue and LA scar, we can now quantify the extent of scarring in distinct LA regions (Figure 4). This could potentially provide further insight into the role of posterior wall scarring in AF termination.

**Understanding the variable response rates to AF ablation**

The use of DE-MRI to analyze postprocedure data has shown a wide variability in the extent of lesion formation seen amongst AF patients following ablation. Figure 5 depicts the different degree of scarring seen in three patients using a similar ablation strategy with consistent procedure parameters. Owing to the variable clinical responses of patients following AF ablation, much of the current research with DE-MRI is focused on why certain patients respond to catheter ablation when others do not. Recent findings from our group indicate that patients with extensive structural remodeling of their LA have significantly less scar formation at 3 months following the procedure [38]. Although an explanation of this phenomenon remains unclear, we speculate that patients with extensively diseased LA have histopathological characteristics, such as high amounts of fibrosis, which inhibit permanent scar formation [40]. The variable response

Figure 4. Quantification of left atrial scar can be achieved with a threshold-based algorithm. This is accomplished by tracing the left atrial wall (left) then creating a histogram of the pixel intensity distribution. Scar tissue is defined at a standard deviation of 3 from the normal left atrial tissue.

Figure 5. Variable scar formation that occurs amongst atrial fibrillation patients following catheter ablation. The patient on the left demonstrates minimal posterior wall scarring compared with the patient on the right. Understanding what factors influence left atrial scar formation could potentially be valuable in achieving a better understanding of the high procedure failure rates amongst certain groups of atrial fibrillation patients.
of scar formation might be the factor responsible for procedure failure (i.e., even if consistent RF parameters are used, certain LA substrates may not respond appropriately to the RF energy and may be more resistant to scar formation). Whether this is due to pre-existent fibrosis, or other factors, such as LA wall thickness, it nonetheless opens the question that individual ability to scar could be the most important prognostic indicator of procedure success.

The future role of real-time MRI in the catheter ablation

Real-time MRI is a potentially revolutionary electrophysiology study. However, great advances need to be made before real-time MRI replaces fluoroscopy as an imaging tool in electrophysiology studies. Primarily, the safety of this method needs to be assessed and technical issues still remain, including optimal designs of catheters that could be used and visualized in this system.

Conclusion

Recent technical advancements in cardiac imaging have resulted in the increased use of DE-MRI in the clinical management of AF. This has resulted in the use of DE-MRI as a noninvasive modality to provide more understanding regarding the underlying pathophysiology of AF, as well as providing more knowledge regarding the postablation effects of interventional treatment strategies. At our institution, we have begun implementing the use of DE-MRI into clinical practice for these matters. This includes ongoing projects analyzing postablation scar patterns of PV antrum isolation and posterior wall debulking and assessments of scar characteristics associated with AF termination. Currently, we are routinely acquiring 3 month follow-up MRI in order to assess whether procedure end points were met, as well to determine which LA regions require additional scar during repeat procedure. We are also currently using DE-MRI to assess the severity of AF disease as a screening tool to select proper ablation candidates. Future direction of this technology includes implementing real-time MRI into the electrophysiology laboratory. This modality would allow a real-time assessment regarding extent and location of LA thermal injury with clear and accurate visualization. This next step holds the potential to drastically alter the ability to treat and cure this arrhythmia.

Executive summary

Visualization of radiofrequency-induced scar following atrial fibrillation ablation

- Recent improvements in temporal and spatial resolution of cardiac MRI has allowed for the unique visualization of ablation-induced scar postprocedure. These data provide a unique insight in regards to the left atrial response from catheter ablation.

Analysis of catheter ablation scar patterns

- Generation of 3D delayed enhancement MRI (DE-MRI) models of the left atrial (LA) postablation has the ability to show the location and integrity of scar following the procedure. This information can be used to assess when complete and continuous pulmonary vein antrum lesions were obtained.
- Correlation of postablation scar patterns with clinical outcome may provide better insight regarding the ablation techniques that are most appropriate for different atrial fibrillation (AF) patients.

Use of DE-MRI to assist in AF ablation

- DE-MRI can accurately and noninvasively locate breaks in ablation lesions that might be responsible for AF recurrence. These gaps can then be targeted during repeat procedure in order to ensure contiguous ablation lesions around the pulmonary vein antrum.

Quantification of LA scarring postablation

- Quantification of scar and correlation with clinical outcome using DE-MRI could provide further insight as to whether new ablation techniques, such as LA debulking, are appropriate in certain AF cohorts.

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Role of delayed enhancement MRI in atrial fibrillation ablation

Review


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