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Dynamic T2 Signal Changes on MRI after Radiofrequency Ablation Injury to the Atrial Myocardium

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Abstract

Purpose: Radiofrequency Ablation (RFA) is an effective therapy for Atrial Fibrillation (AF) and can result in cure. Post-ablation injury is well visualized on T2 Weighted (T2w) Cardiac Magnetic Resonance Imaging (CMRI) sequences but does not correlate well with scar formation. However, the change in T2 signal over time has not been well described and may still prove to be clinically useful.

Methods and Results: A total of 29 patients presenting for Pulmonary Vein Isolation (PVI) for the treatment of AF underwent serial T2w CMRI before and after the procedure. Immediate RFA lesions were characterized by T2w imaging during CMRI guided ablations in a porcine model (6 pigs). All ablation procedures were performed in an Electrophysiology-Magnetic Resonance Imaging (EP-MRI) suite with an imaging on a 3 Tesla scanner. Study of the Left Atrial (LA) injury response on CMRI scans showed increased T2w signal seconds after ablation, involved a majority of the LA wall within 24 hours, and resolved in less than a week.

Conclusion: RFA injury to the LA myocardium causes inflammatory changes on T2w MRI that begin immediately after energy delivery and spread rapidly to the surrounding tissue. These MRI findings may be of clinical interest as tissue injury from the initial RFA lesions may influence the success of lesions delivered later in the procedure.

Keywords: Radiofrequency Ablation; T2; Cardiac MRI; Atrial Fibrillation

Introduction

Catheter ablation of Atrial Fibrillation (AF) has evolved significantly over the last 15 years and is now an established and effective therapy for common arrhythmia [1,2]. The use of Radiofrequency ablation (RFA) techniques to achieve Pulmonary Vein Isolation (PVI) is guided by x-ray fluoroscopy with tissue viability and lesion localization provided by Electroanatomical Mapping (EAM) systems. Post-ablation injuries to the Left Atrium (LA) have been studied with Magnetic Resonance Imaging (MRI) using both Late Gadolinium Enhancement (LGE) and T2-Weighted (T2w) imaging sequences [3,4]. The late post-ablation scar that results from ablation injury to the myocardium can be visualized on LGE MRI and has been described previously [5,6,7]. More recently, there has been increasing interest in visualizing the immediate post ablation injury to better understand its effect on LA remodeling and the success of the procedure [8]. Within 24 hours post-ablation, dark regions of no-reflow on LGE MRI have been shown to correlate with regions of myocardium that eventually become scarred [9,10]. Study of the acute ablation injury using T2w sequences also has been described. Within 24 hours post-ablation, increased T2 signal is seen in regions with injuries both transient (edema and inflammation) and permanent (tissue necrosis becoming scar) [7,11,12,13]. As a result, post-ablation T2 signal is not seen as a good predictor of subsequent scar formation [14].

While post-ablation T2 signal has been shown to increase and even expand beyond the sites of ablation injury [10,13], the time of onset and resolution of T2 signal following ablation is not well studied. In this paper we describe the temporal course of post-ablation injury on T2w imaging using data from humans and a porcine model. The dynamic T2 signal changes post-ablation and may provide important clinical information when considering the atrial response to RFA injury.

Methods

Patient's data was obtained from the patients in the University of Utah AF Database. From June 2009 to December 2012, patients who underwent PVI with posterior and septal wall debulking in our EP-MRI suite equipped with a 3 Tesla (3T) MRI scanner (Verio, Siemens Healthcare, Erlangen, Germany) were screened for inclusion. A total of 29 patients who had good quality T2w imaging at baseline and post-ablation were included in the analysis. Time points for post-ablation scans ranged from

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<24 hours to 3 months with a maximum of 15 scans included for any one post-ablation time point. Written informed consent was obtained on all patients and the protocol was approved by the Institutional Review Board at the University of Utah and was compliant with the Health Insurance Portability and Accountability Act (HIPAA) of 1996.

Both Two Dimensional Double Inversion Recovery Half Fourier Acquisition With Single-Shot Turbo Spin-Echo (2D DIR-HASTE) and Two Dimensional Double Inversion Recovery Turbo Spin-Echo (2D DIR-TSE) were used to visualize post-ablation injury and edema. These sequences were respiratory navigated and Electrocardiogram (ECG)-gated with data acquisition during LA diastole. DIR-HASTE parameters were: Echo Time (TE)=73ms, Repetition Time (TR)=one respiratory cycle, fat suppression using Spectral Adiabatic Inversion Recovery (SPAIR), in-plane resolution of 1.25x1.98 mm, slice thickness of 4 mm, 24 slices, Generalized Autocalibrating Partially Parallel Acquisitions (GRAPPA) with 2 and 34 reference lines. Typical acquisition time was 2 minutes. DIR-TSE parameters were: TE=83 ms, TR=2RR ECG intervals, Echo Train Length (ETL)=21, fat suppression using SPAIR, in-plane resolution of 1.25x1.25 mm, slice thickness of 4 mm, 20 slices, GRAPPA with R =2 and 42 reference lines. Typical scan time was 6 minutes.

Animal data was obtained from six pigs that underwent MRI guided ablation in the EP-MRI suite as previously described [10]. Briefly, an MRI-compatible ablation catheter (MRI Interventions Inc., Irvine, CA, USA) was advanced into the right or left atrium under real time (RT) MRI guidance. Images during RF energy delivery were acquired using an ECG triggered, respiratory gated, T2w-HASTE sequence with the following parameters: TE=79 ms, TR=1 respiration cycle, 3 contiguous slices with thickness of 4 mm, resolution=1.25×1.78 mm, fat saturation and parallel imaging with R=2. The sequence was optimized for the animal's heart rate, tissue-blood contrast, and fat suppression. Images can be acquired approximately every 2 seconds. Animal protocols were approved by the Institutional Animal Care and Use Committee.

Results

A summary of the number of humans and pigs included in the study and numbers of scans with imaging time points are shown in Table 1.

Table 1: Patients study grouped by available T2-weighted CMR scans. Baseline refers to CMR obtained prior to ablation procedure. Day-of refers to MRI scans obtained on the same day of the ablation; hr denotes hours; mo denotes months.

Imaging Scans	n
Pigs	
Baseline, 10 minutes	6
Patients	
Baseline, day of	4
Baseline, 24hr	5
Baseline, 24hr, 48hr	2
Baseline, day of, 72hr	1
Baseline, day of, 96hr	1
Baseline, day of, 24hr, 10 days	1
Baseline, day of, 3mo	3
Patients without baseline T2 scans	
Day of, 24hr	7
Day of, 3mo	3
Day of, 24hr, 3mo	1
24hr, 72hr	1

Immediate radiofrequency (RF) injury on T2w imaging (pig studies)

In the porcine model, atrial wall injury is detected on dark blood imaging using a fast T2w HASTE sequence seconds after catheter ablation. We demonstrate the immediate injury on MRI by delivering a single lesion to the interatrial septum in a swine model after RFA using a MRI compatible catheter. Seconds after ablation injury, focal T2w signal is seen at the site of RF energy delivery (Figure 1, a-c) with little to no signal in the adjacent tissue. Ten minutes later, repeat imaging shows greater intensity of the T2w signal at the burn site, which has now spread to the surrounding tissue (Figure 1, A-C). The temporal changes in the tissue likely reflect acute edema and inflammation triggered by heat injury, as well as hyperemia from damaged microvasculature.

Injury patterns <24 hours after ablation on T2w imaging (human studies)

Over 100 <24 hour post-ablation scans were available in the database and we included the first 15 for this analysis to define the early inflammatory changes hours after AF ablation. Injury that resulted from multiple lesions delivered during the AF ablation procedure is seen as bright, diffuse signal on T2 imaging in all subjects compared to pre-ablation imaging. This T2 signal reflects not only the local ablation injury but extends beyond regions where RF energy was applied. Though the signal varies in intensity between patients and wall segments, the pattern is similar: in most cases, the injury involves the majority of the LA, while sparing the right atrium (RA) walls beyond the interatrial septum (Figure 2). The thickening and bright Signal Intensity (SI) observed in the LA wall immediately post-ablation are consistent with the wound response to ablation (i.e. edema and inflammation), which has been shown in a previous study to appear as a thickened and bright posterior LA wall [6].

Ablation scans were available for 10 patients between 1-7 days, 4 patients between 1-2 weeks, and >100 at three months (included only the first 15). Repeat imaging in the days after the acute injury routinely showed a decrease in T2 signal intensity (Figure 3). The resolution of T2w signal over time varied between patients and may have resulted in part from differences in ablation treatment plan and individual injury response. Complete resolution of T2w signal was seen after the first week in all patients (Figure 4). The reversals of T2 changes over time are evidence of the wound healing response as edema and inflammation resolve.

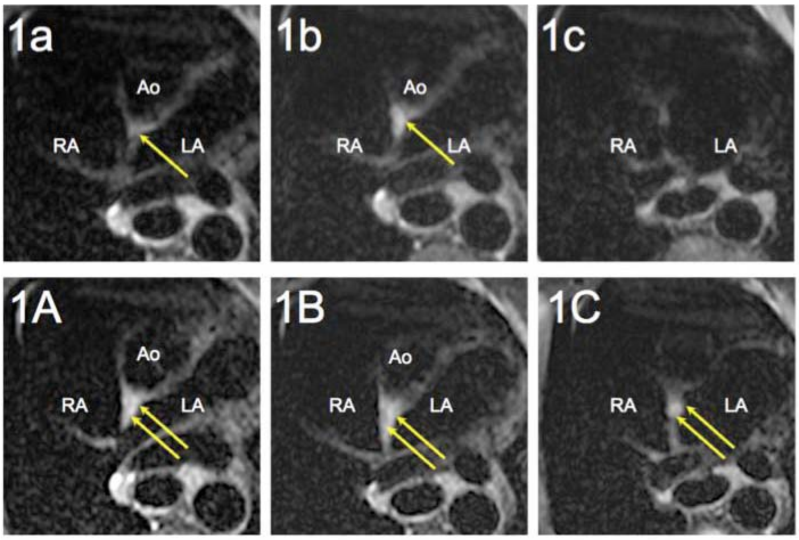

Figure 1: Progression of edema seen after a single RF lesion delivered to the interatrial septum. Matched slices on T2w DIR imaging of pigs immediately after RF ablation (a-c) and again 10 minutes later (A-C).
Top panels with single yellow arrows show immediate injury response as localized, bright T2 signal at the site of energy delivery.
Bottom panels with double arrows show early progression of injury as increasing T2 signal spreads to adjacent tissue.
In C, signal intensity has spread vertically away from the ablation site, toward the base of the heart.
RA = right atrium, LA = left atrium, Ao = aorta.

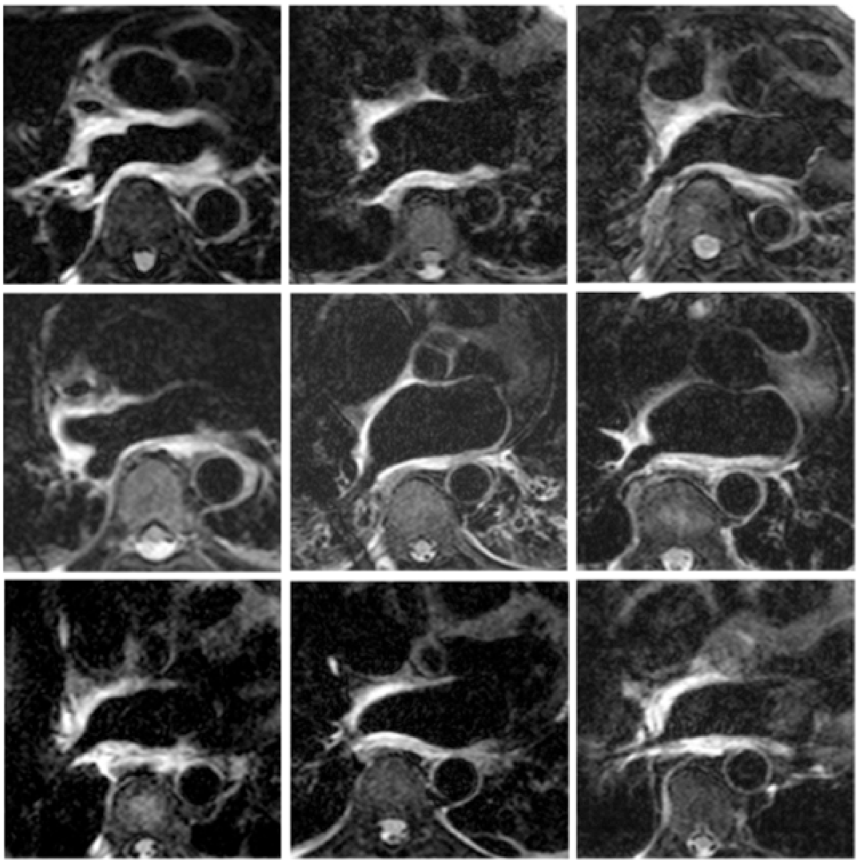

Figure 2: Diffuse LA wall edema after completion of AF ablation procedure.
T2w DIR imaging from 9 patients post ablation shows bright T2 signal spreading throughout the LA.
No significant T2 signal is seen in the RA.

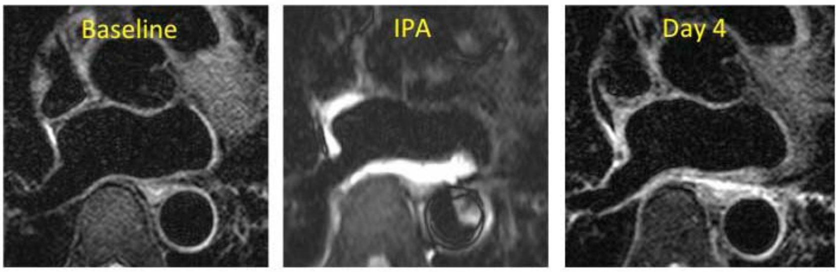

Figure 3: Short term onset of LA wall edema after AF ablation.
T2w DIR imaging from a patient showing baseline LA wall signal that becomes very intense immediately post ablation (IPA) that decreases intensity at 4 days after the ablation.

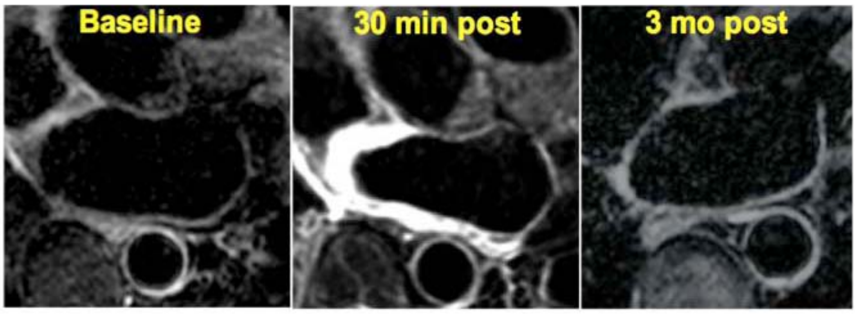

Figure 4: Resolution of LA wall edema after AF ablation.
T2w DIR imaging from a patient comparing baseline sign with bright signal occurring at 30 minutes post ablation and returning to baseline at 3 months

Discussion

In this study, we show the dynamic changes in T2 signal that occur in the seconds, days, and months after ablation injury. Clear increases in T2 signal are seen immediately after delivery of RF energy and can take up to a week to completely recover. Changes in myocardial T2 signal during RFA suggest an early, rapid, and robust response to injury, which may have important consequences for lesion efficacy for burns delivered later in the procedure.

Changes in T2 signal occurring during ablation were studied using a MRI compatible catheter in a porcine model. Seconds after RF energy is delivered, increased T2 signal is seen at the catheter ablation site and quickly spreads (within minutes) to adjacent tissue not in direct contact with the catheter. This early progression of T2 signal in the atrium reflects edema and tissue inflammation. During the inflammatory response, capillaries leak intravascular fluid into the myocardium. This fluid, which has a longer T2 value relative to myocardium, appears brighter on T2 weighted imaging [15]. The bright appearing tissue on T2w imaging includes both regions of transient injury and necrosis. Earlier studies have shown that T2 signal persists up to 12 hours after ablation, but have not demonstrated resolution of T2w signal over longer periods of time [16]. For this reason, previous studies have concluded that post ablation T2 signal is not a good predictor of late scar formation [13,14].

Over the subsequent week after ablation, T2 signal in the atrium returns to baseline. Resolution of the acute T2 changes over this recovery period occurs, relatively slowly compared to the immediate, intense T2 signal increase was seen during the ablation procedure. Data from patients with follow up imaging 1-7 days post-ablation showed the return to baseline occurring at differing rates. In some patients, T2 signal is back to baseline within 2 days. While in others, some degree of T2 signal increase can persist up to 6 days post-procedure. The differences seen in T2 signal recovery may be due to variables such as the amount of tissue ablated and individual tissue inflammatory responses.

The ability to achieve LA scarring after ablation injury is a key determinant for a successful procedure outcome. Currently, low voltage on EAM remains the standard for determining scar formation after RFA injury. A recent study demonstrates that EAM overestimates the actual scar formed when compared to LGE-MRI [17]. One possible reason for this is the effect of the RF energy on the adjacent tissue. As more energy is applied during the procedure the surrounding tissue becomes more inflamed and edematous, which may result in less effective energy delivery to tissue with each subsequent burn. Reversible tissue changes may result in low voltage signal on EAM and be interpreted incorrectly as necrotic or scarred tissue. Thus, operators should be cognizant of the possibility that low voltage does not necessarily equate with necrosis and that RFA lesions delivered later in the procedure may be less effective.

Study Limitations

a. The T2w imaging data acquired immediately post-ablation are from a swine model and may not reflect tissue response to ablation in humans. Acquiring MRI during an ablation procedure in humans was not feasible.

b. T2 signal changes were assessed visually over time and quantitation of signal intensity was not performed. However, the clinically relevant tissue changes described here can be visualized clearly on MRI, one of the advantages of this imaging sequence.

c. While a large number of patients in our database had baseline, 24hr, and 3-month post-ablation studies, a far smaller number underwent T2w imaging at intermediate time points.

Conclusions

In conclusion, RFA injury to the LA myocardium causes tissue injury seen immediately after ablation on T2w MRI. This process is dynamic involves nearly the entire LA wall <24 hours after ablation injury. Days after ablation, T2 signal changes resolved before returning to baseline after one week. The immediate tissue response to ablation injury may be of clinical interest as low voltage on EAM may not identify only necrotic tissue and early RFA lesions may influence the success of lesions delivered later in the procedure.

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Declarations

The authors certify that there is no conflict of interest with any financial, research or academic organization, with regards to the content/research work discussed in the manuscript.

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