Atrial Fibrillation Ablation Outcome Is Predicted by Left Atrial Remodeling on MRI

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Background—Although catheter ablation therapy for atrial fibrillation (AF) is becoming more common, results vary widely, and patient selection criteria remain poorly defined. We hypothesized that late gadolinium enhancement MRI (LGE-MRI) can identify left atrial (LA) wall structural remodeling (SRM) and stratify patients who are likely or not to benefit from ablation therapy.

Methods and Results—LGE-MRI was performed on 426 consecutive patients with AF without contraindications to MRI before undergoing their first ablation procedure and on 21 non-AF control subjects. Patients were categorized by SRM stage (I–IV) based on the percentage of LA wall enhancement for correlation with procedure outcomes. Histological validation of SRM was performed comparing LGE-MRI with surgical biopsy. A total of 386 patients (91%) with adequate LGE-MRI scans were included in the study. After ablation, 123 patients (31.9%) experienced recurrent atrial arrhythmias during the 1-year follow-up. Recurrent arrhythmias (failed ablations) occurred at higher SRM stages with 28 of 133 (21.0%) in stage I, 40 of 140 (29.3%) in stage II, 24 of 71 (33.8%) in stage III, and 30 of 42 (71.4%) in stage IV. In multivariate analysis, ablation outcome was best predicted by advanced SRM stage (hazard ratio, 4.89; \( P<0.0001 \)) and diabetes mellitus (hazard ratio, 1.64; \( P=0.036 \)), whereas increased LA volume and persistent AF were not significant predictors. LA wall enhancement was significantly greater in patients with AF versus non-AF controls (16.6±11.2% versus 3.1±1.9%; \( P<0.0001 \)). Histological evidence of remodeling from surgical biopsy specimens correlated with SRM on LGE-MRI.

Conclusions—Atrial SRM is identified on LGE-MRI, and extensive LGE (≥30% LA wall enhancement) predicts poor response to catheter ablation therapy for AF. (Circ Arrhythm Electrophysiol. 2014;7:23-30.)

Key Words: atrial remodeling • catheter ablation • magnetic resonance imaging

Atrial fibrillation (AF) is the most common sustained arrhythmia in clinical practice, with its prevalence increasing along with the age of the population.1,2 It occurs in 1% to 2% of the general population, and the lifetime risk for development of AF in the Framingham cohort was 25% among those >40 years of age.3 The clinical consequences of AF are well known and include increased risk of heart failure, stroke, and death.4 Increased risk for the development of AF has been associated with factors such as age, hypertension, and obesity,5–8 but more specific and early markers for disease could have important clinical impact.

Several large clinical trials have shown no significant benefits of rhythm control strategies using antiarrhythmic medications compared with rate control alone in the treatment for AF.9–12 As a result, the morbidity and mortality associated with AF remain largely unchanged along with the associated medical costs, which are estimated to be >6 billion dollars annually in the United States and Europe alone. Given the limitations of antiarrhythmic medications, there has been growing interest in the treatment of AF with catheter ablation because of improvements in efficacy and outcomes.13–17 However, reported success rates for AF ablation vary widely in the published literature ranging from 40% to 70% and suggest a need for better patient selection criteria.18

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Atrial structural remodeling (SRM) with associated interstitial fibrosis is well described in patients with AF in histological studies.\textsuperscript{19–23} Tissue examination of the left atrium (LA) has also confirmed the presence of fibrosis in regions of low-voltage tissue.\textsuperscript{24} Whether fibrotic transformation of atrial myocardium is a cause or consequence of AF in patients with cardiovascular disease remains unclear. Studies have demonstrated that AF is associated with electric, contractile, and structural remodeling in the LA that contributes to the persistence and sustainability of the arrhythmia.\textsuperscript{25} It has also been shown that the end result of this remodeling process is loss of atrial myocytes and increased collagen content and hence fibrosis of the LA wall. Previous small electrophysiology and imaging studies have shown low-voltage and fibrotic LA tissue as independent predictors of procedure outcome and suggest that an accurate and reliable measure of LA fibrosis may improve clinical decision making.\textsuperscript{26–27} Better patient selection criteria would be expected to improve procedure outcomes while reducing costs and avoiding potential complications in those unlikely to benefit from ablation.

In the current study, we tested the hypothesis that late gadolinium enhancement MRI (LGE-MRI) can provide a measure of LA wall SRM in patients with AF and will stratify those unlikely to benefit from ablation.

**Methods**

**Patients**

The study population included 426 consecutive patients without contraindications to MRI who underwent their first AF ablation procedure, 21 control subjects, 9 patients with AF, and 1 non-AF patient who had LA wall biopsies during cardiothoracic surgical procedures. The control group comprised a series of consecutive patients presenting for routine screening colonoscopy (21 patients), none of whom had a history of AF. The AF study population was recruited from the AF clinic from December 2006 to May 2009 with 3-year follow-up. Statistical analysis of the data focuses on the 1-year follow-up when recurrences were based on routine, scheduled Holter monitoring in all patients (see details of follow-up below). The control and surgical groups were recruited from August 2010 to December 2011. Written informed consent was obtained from 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 of 1996.

**MRI**

All subjects underwent initial 3-dimensional (3D) LGE-MRI scanning to determine the degree of LA wall SRM, regardless of the rhythm at the time of scanning. Adequate images for quantification of LA wall SRM was obtained in 386 of 426 patients in the AF ablation cohort (91%), all control subjects, and all surgical patients. High-resolution LGE images of LA were acquired ≈15 minutes after injection of 0.1 mmol/kg gadolinium contrast (Multihance, Bracco Diagnostics Inc, Princeton, NJ) using a 3D respiratory-navigated, inversion recovery–prepared GRE pulse sequence with specific parameters published previously.\textsuperscript{28–30} The specific parameters for MR scanning at 1.5 versus 3T are provided in the Data Supplement. Briefly, for this 3D respiratory-navigated, ECG-gated, inversion recovery–prepared GRE pulse sequence, an inversion preparation was applied every heart beat, and fat saturation was applied immediately before data acquisition. The voxel size is 1.25×1.25×2.5 mm on both 1.5-T and 3-T scanners.

Although prescan ECGs were not routinely obtained, the rhythm status is always clarified at the time of MRI scanning by the technologist and reading physician by use of the ECG gating from the scanner and, if necessary, by evaluating the cine images. By these criteria, 67% of the study patients appeared in sinus rhythm at the time of scanning. Of the 40 patients with inadequate scans, artifacts because of patient motion, marked arrhythmias, or gating problems were the main contributing factors. Scanning was performed on a 1.5-T Avanto (286 patients) or a 3-T Verio (100 patients) MR scanner (Siemens Healthcare, Erlangen, Germany).

**LGE-MRI Assessment of LA SRM**

LA wall volumes were manually segmented by 3 trained observers from the LGE-MRI images using the Corview image processing software (Merrek Inc, Salt Lake City, UT). The MRI scans were deidtified, and observers were blinded to whether scans were performed on control subjects, patients with AF, or surgical patients. The protocol for segmentation proceeded as follows. First, the endocardial border of the LA was defined, including an extent of pulmonary vein (PV) sleeves, by manually tracing the LA–PV blood pool in each slice of the LGE-MRI volume. Next, the endocardial segmentation was morphologically dilated and then manually adjusted to create an assessment of the boundary of the epicardial LA surface. Finally, the endocardial segmentation was subtracted from the epicardial segmentation to define a wall segmentation, which was manually edited to exclude the mitral valve and PVs. Thus, the resulting LA wall segmentation included the 3D extent of both the LA wall and the antral regions of the PVs (Figure 1).

Quantification of LA remodeling was obtained using the methods previously described with the addition of software implemented in Corview to improve determination of MRI intensity values.\textsuperscript{29} Typically, enhancement values are found to be in the range of 2 to 4 SDs from the mean value. Once the threshold has been determined, the percentage of enhancement is calculated as the number of voxels in the LA wall segmentation with values above the threshold divided by the total number of voxels in the LA wall segmentation. The study patients were then assigned to 1 of 4 SRM categories based on LA wall enhancement as a percentage of the total LA wall volume, with stage I defined as <10%, stage II ≥10% to 20%, stage III ≥20% to 30%, and stage IV ≥30%. Additional details on methods for quantification of LA remodeling are provided in the Data Supplement.

**Ablation Procedure and Follow-Up**

The details of the PV isolation, in addition to posterior wall and septal debulking, have been described elsewhere.\textsuperscript{30} A 10-pole circular mapping Lasso catheter and a 3.5-mm Thermocool ablation catheter ( Biosense Webster, Diamond Bar, CA) were used, and radiofrequency energy was delivered with 50 W at a catheter tip temperature of 50°C for 5 seconds, guided by electrogram ablation recordings.

**Figure 1.** Segmentation process used for quantification of left atrial (LA) wall fibrosis. A, Single slice level from 3-dimensional (3D) late gadolinium enhancement data set before ablation. B, Endo and epic contours of the LA wall used for determining degree of fibrosis. C, Abnormal fibrotic regions in green and normal nonfibrotic tissue in blue. D, Three-dimensional reconstruction of the entire data set separated to highlight the specific slice level in this example.
After ablation, recurrences in year 1 were determined by 8-day Holter monitoring performed on patients at 3, 6, and 12 months, patient reporting, and all ECG data. In years 2 and 3, follow-up was based on symptom-guided Holter monitoring and ECG data during clinic follow-up. Atrial arrhythmia recurrence after ablation was defined using the Heart Rhythm Society consensus document on catheter and surgical ablation of AF \cite{10,11} and required the presence of 30 seconds of atrial arrhythmia after a 90-day blanking period. Additional details are provided in the Data Supplement.

**Surgical Biopsies and Histochemical Stains**

Myocardial tissue was obtained from the LA at the time of cardiac surgery in 9 patients with AF and 1 non-AF patient. All patients underwent cardiac MRI/magnetic resonance angiography scans before surgery. The surgeon obtaining the biopsy specimens marked the biopsy location on an interactive 3D magnetic resonance angiography of the LA for each subject, which was then overlaid on the 3D LGE-MRI to correlate the surgical biopsy site with LA wall tissue on MRI. The LA biopsy tissue was formalin-fixed and paraffin-embedded. Evaluation for collagen content was performed using Masson trichrome stain. Details of whole-field digital microscopy \cite{32} are provided in the Data Supplement.

**Statistics**

Statistical analysis was performed using STATA12 (Statacorp, College Station, TX). LA wall SRM was reported as a continuous variable with mean±SD. Other continuous variables included age, LA volume, and left ventricular ejection fraction. Categorical variables included sex and medical comorbidities. An unpaired 2-sided Student t test was used for multiple means comparison between SRM groups. A \( \chi^2 \) test was used to evaluate differences in categorical variables across different stages. A Fisher exact test was used to evaluate differences within the control group and the control group. Survival analysis using Cox proportional hazards model was used to identify univariate and multivariate recurrence predictors. Statistical interaction was examined by including interaction terms, specifically for clinical variables correlated with atrial SRM. The interaction terms did not alter the results of statistical association and are not displayed. A value of \( P<0.05 \) was considered statistically significant. Interobserver variability was calculated using the Pearson correlation coefficient.

**Results**

**Study Patients and Association With SRM Stages**

A comparison of baseline characteristics of patients with AF across SRM stages is provided in Table 1. Patients with AF distributed into 4 SRM categories based on the percentage of LA wall enhancement on LGE-MRI as follows: 133 (34.5%) stage I, 140 (36.3%) stage II, 71 (18.4%) stage III, and 42 (10.9%) stage IV. Advanced SRM stage was associated with increased LA volume index. When comparing SRM stage with classification according to AF clinical phenotypes, the prevalence of persistent AF increased with higher SRM stage, whereas the prevalence of paroxysmal AF decreased. However, for any individual patient, SRM stage was not predicted by clinical phenotype alone because each stage showed a heterogeneous mix of phenotypes. Also noteworthy, within our study population, we found 13 patients with long-standing persistent AF of >1 year. The average fibrosis for patients categorized this way was 19.5±21.6 versus 18.7±11.5 for persistent AF (\( P=0.9 \)). However, there were simply not enough patients in the long-standing persistent group to deduce any

<table>
<thead>
<tr>
<th>Stage</th>
<th>n=133</th>
<th>n=140</th>
<th>n=71</th>
<th>n=42</th>
<th>P Value</th>
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<td>Age, y</td>
<td>63±13</td>
<td>65±11</td>
<td>66±13</td>
<td>67±12</td>
<td>0.17</td>
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<tr>
<td>Women, %</td>
<td>33.8</td>
<td>30.7</td>
<td>42.3</td>
<td>47.6</td>
<td>0.06</td>
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<tr>
<td>Hypertension, %</td>
<td>62.9</td>
<td>61.4</td>
<td>57.8</td>
<td>66.7</td>
<td>0.81</td>
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<tr>
<td>Diabetes mellitus, %</td>
<td>11.4</td>
<td>12.9</td>
<td>21.1</td>
<td>21.4</td>
<td>0.08</td>
</tr>
<tr>
<td>Coronary disease, %</td>
<td>13.6</td>
<td>12.5</td>
<td>24.4</td>
<td>14.3</td>
<td>0.10</td>
</tr>
<tr>
<td>Congestive heart failure, %</td>
<td>6.1</td>
<td>13.0</td>
<td>12.7</td>
<td>7.1</td>
<td>0.41</td>
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<tr>
<td>LV ejection fraction, %</td>
<td>58±12</td>
<td>59±10</td>
<td>57±12</td>
<td>56±13</td>
<td>0.16</td>
</tr>
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<td>CVA/TIA, %</td>
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<td>11.3</td>
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<td>0.03</td>
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<tr>
<td>Paroxysmal AF, %</td>
<td>61.7</td>
<td>46.4</td>
<td>49.3</td>
<td>26.2</td>
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<tr>
<td>Persistent AF, %</td>
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<td>53.6</td>
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<td>73.8</td>
<td>0.002</td>
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<tr>
<td>Previous AAD use (%)</td>
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<td>12.9</td>
<td>18.5</td>
<td>15.0</td>
<td>0.11</td>
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<tr>
<td>Atrial volume/LA, mL/m²</td>
<td>48±18</td>
<td>51±18</td>
<td>52±21</td>
<td>64±24</td>
<td>&lt;0.0001</td>
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<tr>
<td>LA fibrosis, %</td>
<td>6.7±2.0</td>
<td>15.2±2.9</td>
<td>23.3±2.8</td>
<td>40.9±10.4</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

**Study Patients Compared With Control Groups**

The AF study patients were compared with a control group, without history of AF, consisting of a series of consecutive patients presenting for routine screening colonoscopy. LA SRM with percent wall enhancement on LGE-MRI was significantly greater in the patient group compared with the control group (16.6±11.2% versus 3.1±1.9%; \( P<0.0001 \)). Although the patients with AF were dispersed across all SRM stages (as noted above), all control patients were categorized in stage I. Comparisons of other characteristics between patients with AF and controls showed that LA volume was significantly increased in the AF group compared with the control group (103±41 versus 62±21 mL; \( P<0.0001 \)). Patients with AF were also significantly older and had a higher prevalence of hypertension. A detailed summary of baseline characteristics of these groups is provided in Table 2.

**Predictors of AF Ablation Outcome**

All 386 patients underwent a single ablation procedure for treatment of AF, and 123 patients (31.9%) experienced recurrent atrial arrhythmias at 1-year follow-up. Kaplan–Meier analysis showed that recurrent arrhythmias (failed ablations) occurred in patients with higher SRM scores, with 28 of 133 (21.0%) in stage I, 41 of 140 (29.3%) in stage II, 24 of 71 (33.8%) in stage III, and 30 of 42 (71.4%) in stage IV. For those who experienced recurrent arrhythmia within the first year of follow-up, the median time to recurrence was 142 days. The strong association between atrial SRM stage and arrhythmia recurrence after ablation therapy is shown graphically in Figure 3.
We performed univariate and multivariate analysis to identify significant predictors of arrhythmia recurrence. In the univariate analysis, LA volume increase for each 10 mL/m² (hazard ratio [HR], 1.16; \( P = 0.0001 \)), age for each 10-year increase (HR, 1.22; \( P = 0.011 \)), hypertension (HR, 1.61; \( P = 0.016 \)), diabetes mellitus (HR, 1.80; \( P = 0.006 \)), and persistent AF (HR, 1.47; \( P = 0.014 \)) were associated with arrhythmia recurrence. Compared with patients with stage I SRM, stage IV patients had the highest risk of arrhythmia recurrence (HR, 5.47; \( P < 0.0001 \)) followed by stage III patients (HR, 1.65; \( P = 0.069 \)). In the multivariate model, SRM stage IV was associated with the highest risk of recurrence (HR, 4.89 compared with SRM stage I; \( P < 0.0001 \)). Diabetes mellitus was another significant predictor of arrhythmia recurrence (HR, 1.64; \( P = 0.036 \)). The results of the univariate and multivariate Cox regressions are summarized in Table 3.

After the first year, arrhythmia recurrence was diagnosed on the basis of patient symptom–guided Holter monitoring and ECG data during clinic follow-up for 2 additional years. When we analyzed the data of the 3-year period (mean follow-up, 746±428 days), we found that 169 patients (43.8%) experienced recurrent atrial arrhythmias. Similar to the 1-year outcomes, recurrent arrhythmias occurred in patients with higher SRM scores, with 44 of 133 (33.1%) in stage I, 58 of 140 (41.4%) in stage II, 34 of 71 (47.9%) in stage III, and 33 of 42 (78.6%) in stage IV.

**Histological Basis for LA Wall Fibrosis**

Tissue characterization of the LA wall on LGE-MRI correlated with histology from surgical biopsy specimens. A total of 14 biopsies were taken from 10 surgical patients with histories of AF. Nine biopsy locations showed evidence of significant interstitial fibrosis on Masson trichrome staining and 5 locations showing normal LA wall tissue or minimal collagen staining. LA wall biopsies demonstrating tissue fibrosis matched with regions of LA wall enhancement on MRI.
whereas normal biopsy tissue corresponded with nonenhanced regions on MRI. Furthermore, in a surgical patient without AF and with normal-sized LA, no significant atrial wall enhancement was seen on LGE-MRI and biopsy-confirmed tissue without significant interstitial fibrosis (Figure 4).

**Interobserver Reproducibility**

Atrial fibrosis on MRI scans was analyzed and quantified by 3 blinded observers on a subset of 170 patients randomly selected from the entire cohort. The calculated mean fibrosis values among the 3 observers were not significantly different, and the correlation coefficients ranged from 0.79 to 0.97, indicating a high degree of reproducibility. The high degree of correlation reflects the good scan quality visualization of the LA wall and the experience of the operators in our laboratory who perform these tracings on a regular basis with the aid of computer processing tools.

**Discussion**

We report that LGE-MRI can detect SRM in patients with AF when healthy atrial myocardium becomes fibrotic. For catheter ablation of AF, restoration of sinus rhythm is shown
significantly less likely as the remodeling process advances. These findings suggest that MRI can improve the selection process and outcome for patients being considered for AF ablation procedures.

The results here build on previous work showing LGE-MRI as an important tool in the evaluation of LA fibrosis.26,27,29,33 Although LGE-MRI is a well-established method for characterizing fibrosis and tissue remodeling in the ventricle,34–36 limitations in spatial resolution have made imaging the LA wall more challenging. Recent advancements in navigated 3D MRI now yield greater signal and improved resolution with the ability to locate and quantify atrial remodeling. Data here lend validation of the LA remodeling process on LGE-MRI with clear distinctions between control and patients with AF. Specifically, the AF patient cohort demonstrated a >4-fold increase in percentage of LA wall enhancement over the control group. Furthermore, we show that LA wall biopsy specimens with varying degrees of interstitial fibrosis correlate with findings on LGE-MRI in patients with AF. Although previous surgical studies have demonstrated LA SRM on histological examination of biopsies from patients with AF,23,37,38 we report that tissue enhancement on LGE-MRI reflects SRM changes. These results support the use of MRI for noninvasive assessment of the remodeling process.

The amount of LA wall fibrosis on LGE-MRI strongly correlates with AF ablation outcome, which is the central finding in this study. Arrhythmia recurrence is significantly higher when ≥30% fibrosis (IV patients) is present on preprocedural MRI scans. Scores <30% identify patients far more likely to benefit from catheter ablation procedures. In multivariate analysis, SRM stage was clearly the strongest predictor of ablation outcomes. Patients with ≥30% enhancement on MRI (SRM stage IV) demonstrated poor procedure outcomes with >70% failure rate. These data support previous studies showing that pre-existing low-voltage tissue and scarring in the LA determined invasively during electrophysiology studies are independent predictors of ablation procedure failure and arrhythmia recurrence.39 The presence of low-voltage fibrotic tissue seems to result in abnormal atrial activation, which may underlie the initiation and maintenance of fibrillation.40-42 Both animal and human studies have repeatedly shown that atrial fibrosis can lead to AF through mechanisms that cause alterations in fibrillatory dynamics.40-42 By altering the LA substrate, fibrotic change and SRM probably aid in the formation of circuits needed for re-entry, thus perpetuating the atrial arrhythmia. Because the fibrotic process becomes more advanced, our data support the notion that the fibrillatory circuits increase and become more extensive, thereby making it increasingly difficult to restore sinus rhythm. Interrupting the fibrillatory pathways in the early stages of fibrosis seems to be important for the success of ablation procedures because patients in the earliest remodeling stages (stages I and II) showed higher success rates of 66.9% and 58.6%, respectively.

The hallmark of SRM is atrial fibrosis, a factor leading to persistence of AF. However, whether fibrosis is a cause or result of AF remains a subject of debate. Data here show significant SRM changes on LGE-MRI in patients with AF but not in control populations without AF. In addition, the fibrosis stage correlates with AF clinical phenotype, with more advanced remodeling seen in persistent forms of AF. These findings support previous studies showing that increasing AF burden leads to structural and functional remodeling.43 Progressive structural changes in the atria seen as paroxysmal AF eventually becomes persistent or permanent AF, and conversion to sinus rhythm can lead to reversal of these changes.44-46 These data support a mechanism for atrial fibrosis that results from AF and the notion that AF begets AF.47

Alternatively, atrial SRM can result from other disease processes such as valvular heart disease (eg, mitral stenosis) or heart failure.48-50 In such cases, the fibrotic process seems to precede the development of AF. To better understand the fundamental association between fibrosis and AF, surveillance imaging of the LA in populations with and without AF could help enhance our understanding of the fibrotic process and its consequences in cardiovascular disease states. Our best understanding of the currently available literature points to more than one mechanism, including accelerated LA fibrosis resulting from AF or from fibrotic processes (eg, structural disease) leading to AF.

Our study is limited as it is a single-center, observational study. In addition, to perform quality 3D LGE-MRI studies routinely in patients requires a high level of expertise in MRI and support during the studies by expert MR imagers and technologists. Processing of the MR images is laborious and requires experienced observers to perform the LA wall tracings and to select the threshold levels. Improvements in image processing and automatization of the process are possible and are expected to simplify and help further standardize the image processing. In addition, the operators performing the AF ablation procedures were not blinded to the results of the MRI scan. Knowledge of the fibrosis score could have led to biases in their approach to the ablation procedure.

Noninvasive evaluation of myocardial tissue using LGE-MRI is a powerful tool for detecting and quantifying atrial tissue disease and changes that result from the SRM process. In patients with AF, the degree of the LA wall SRM predicts response to catheter ablation therapy, with restoration of sinus rhythm highly unlikely in patients with advanced remodeling stage. Currently, the selection process for ablation procedures remains somewhat subjective, with failed antiarrhythmic drug therapy, clinical phenotype, and patient treatment preferences all taken into consideration. With better and more stringent selection criteria, we can improve outcomes and cost-effectiveness by avoiding ablation procedures unlikely to benefit patients with AF.

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Disclosures
N.F.M. is a board member of Merrek.
References


This article builds a strong case that MRI is a useful clinical tool for identifying preprocedural left atrial structural remodeling in patients with atrial fibrillation (AF). We present 1-year outcome data on 426 consecutive patients with AF who underwent 3-dimensional late gadolinium enhancement MRI studies before ablation therapy. Data here show that late gadolinium enhancement MRI is a powerful tool for identifying patients with AF likely or not to benefit from ablation therapy. Currently, the selection process for ablation procedures remains somewhat subjective, with failed antiarrhythmic drug therapy, clinical AF phenotype, and patient treatment preferences all taken into consideration. We think that the data here will help improve the selection criteria for AF ablation and in turn improve outcomes and cost-effectiveness of the procedure.
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Methods

**Magnetic resonance imaging.** Details for the 3D LGE-MRI imaging for left atrial fibrosis at 1.5T and 3T are as follows: for the patient in sinus rhythm, data acquisition was performed during LA diastole. Specifically, data acquisition window was 15% of averaged cardiac cycle (aRR) and it was positioned from 65% to 80% of aRR (0% corresponds to peak of R-wave). For AF patients with non-regular heart rate during the imaging session, the duration of data acquisition window was reduced to 12% of aRR and it was shifted closer to the R-wave and positioned from 47% to 59% of aRR. Other scan parameters for LGE of LA at 3T scanner were: axial imaging volume, FOV=400x400x110 mm, voxel size=1.25x1.25x2.5 mm, TR/TE=3.1/1.4 ms, flip angle of 14 degrees. Scan parameters for LGE of LA at 1.5T scanner were: axial image volume, FOV=360x360x100 mm, voxel size=1.25x1.25x2.5 mm, TR/TE=5.2/2.4 ms, flip angle of 20 degrees. Typical scan time for LGE study was 6-12 minutes at 1.5 and 5-9 minutes 3T scanner depending on patient respiration.

**LGE-MRI assessment of left atrial structural remodeling.** As noted in the manuscript, quantification of LA remodeling was obtained using the methods previously described with the addition of software implemented in Corview to improve determination of MRI intensity values. Some important details are as follows. After segmentation of the LA wall (see methods in manuscript and Figure 1), next we estimate an intensity threshold
for enhancement (fibrosis) by inspection with an interactive intensity thresholding tool within Corview. The thresholding tool displays the mean and standard deviations of the MRI voxel values in the LA wall on top of a histogram of the wall intensity values. The user then selects a threshold value for enhancement using a slider. As the threshold slider is moved, the user can see which pixels are being selected in both a 2D display of the MRI image stack and a 3D volume rendering of the MRI. Typically, enhancement values are found to be in the range of 2-4 standard deviations from the mean value. Once the threshold has been determined, the percentage of enhancement is calculated as the number of voxels in the LA wall segmentation with values above the threshold divided by the total number of voxels in the LA wall segmentation.

**Ablation procedure and follow up.** The LA was accessed through two trans-septal punctures under intracardiac echo guidance using a phased array catheter (Acunav, Siemens Medical Solutions USA, Inc, Mountain View, CA). A 10-pole circular mapping catheter (Lasso, Biosense Webster, Diamond Bar, CA) and a 3.5 mm Thermocool ablation catheter (Biosense Webster, Diamond Bar, CA) were advanced into the LA for mapping and ablation. A 14-pole catheter (TZ medical, Portland, OR; Biosense Webster, Diamond Bar, CA) was used to record right atrial and coronary sinus electrograms and was used as the reference catheter for 3D electro-anatomical mapping with CARTO (Biosense Webster, Diamond Bar, CA). Radiofrequency energy was delivered with 50 Watts at a catheter tip temperature of 50 °C for 5 seconds, guided by electrogram abolition recorded on the Lasso catheter. Ablation lesions were placed in a circular fashion in the pulmonary vein antral region until electrical isolation of the pulmonary
veins was achieved. Additional lesions were placed along the LA posterior wall and septum at the discretion of the operator.

**Surgical biopsies and histochemical stains.** *Whole-field digital microscopy:* Advanced digital microscopy allowed examination of the entire heart tissue areas from the epicardium to the endocardium. Whole-slide images were analyzed with the ScanScope XT system equipped with the ImageScope 10.0 image analysis algorithms (Aperio Technologies, Vista, CA)\(^{31}\). *Collagen content evaluation:* we set the staining color threshold of the ImageScope 10.0 Color deconvolution analysis algorithm to accurately identify collagen based on its blue color. Subsequently, myocardial collagen content was determined by running the algorithm on the stained myocardial tissue. “Interstitial Fibrosis” was defined as the collagen content determined in the interstitial spaces and endomysial/perimysial spaces including the collagen content around capillaries and small vessels found within those spaces.

**Tables.**
Kaplan-meier rates of recurrence in paroxysmal AF patients. Percentages of paroxysmal AF patients in each stage are as follows: 61.7 Stage I, 46.4 Stage II, 49.3 Stage III, and 26.2 Stage IV.
Kaplan-meier rates of recurrence in persistent AF patients. Percentages of persistent AF patients in each stage are as follows: 38.4 Stage I, 53.6 Stage II, 50.7 Stage III, and 73.8 Stage IV.