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Cardiac magnetic resonance imaging assessment of regional and global left atrial function before and after catheter ablation for atrial fibrillation

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Abstract
Background Ablation of the left atrium and pulmonary veins antrum (PVAI) can be an effective treatment of atrial fibrillation (AF). However, there is discrepancy in the literature regarding the effect extensive ablation has on left atrial (LA) function. We sought to evaluate the effect that AF ablation procedures has on global and regional wall motion as assessed by cardiovascular magnetic resonance imaging (MRI).
Methods Consecutive patients undergoing PVAI had cardiac MRI performed preablation and 3 months post ablation. Patients included paroxysmal (n=16) and persistent/permanent (n=13). In addition, 12 volunteers underwent cardiac MRI to provide a control population. LA transport function was assessed by obtaining cyclical change indices, total percent emptying, LA stroke volume indices, and LA active percent emptying. Using chordal segment analysis and radial motion of the left atrium, regional motion was assessed throughout the LA emptying cycle.
Results All four PVs were isolated for all patients. Imaging revealed a significant reduction in LA volumes in AF patients post-PVAI. In the subset of patients with persistent AF, post-PVAI improvements were seen in global (p<0.01) and regional LA functions (p=0.01). In the paroxysmal AF patients, post-PVAI measurements revealed decreases in LA transport function (p=0.02) as well as diminished regional function in the LA lateral wall (p=0.02). The paroxysmal AF patients had global and regional LA functions comparable to the normal volunteers prior to ablation; however, these were significantly diminished post ablation.
Conclusion Extensive ablation during PVAI causes mild deterioration in LA function. However, in patients with a high burden of AF, it appears that the positive remodeling that occurs with rhythm restoration outweighs any negative effects of ablation.

Keywords Atrial fibrillation · Catheter ablation · Left atrial function

1 Introduction

Ablation of the posterior left atrial (LA) wall and tissue surrounding the pulmonary veins (PVs) appears to be a safe and effective treatment of atrial fibrillation (AF). As the technique has been applied to a broader patient population, more extensive ablation has been advocated [1–3]. As more aggressive ablative strategies are employed, a threshold may be reached where atrial dysfunction secondary to excessive tissue destruction and associated loss of LA contractility may supersede the benefits gained from rate control and positive atrial remodeling. Data from surgical maze and "mini-maze" operations show that extensive damage to the atrial myocardium may limit the hemodynamic benefit anticipated by restoration of normal sinus rhythm. These reports show that 20–30% of those patients who had restored normal sinus rhythm continued to have atrial dysfunction as assessed by Doppler echocardiography [4, 5]. Studies have attempted to investigate the effect ablation has on atrial function by analyzing atrial dimensions via echocardiography, electron beam computed tomography (EBCT), and magnetic resonance imaging

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(MRI) [6–9]. Each study has consistently showed decreased LA volumes after PV isolation. This occurrence may be the result of positive atrial remodeling after reducing AF burden or may be the result of atrial scarring and tissue retraction. However, conflicting data has been reported when parameters of global LA function are monitored in patients with paroxysmal AF post-PVAI [6, 7, 9]. These studies have examined global LA function only.

It was hypothesized that because the PVs are relatively fixed in anatomical position relative to other mediastinal structures and because the posterior LA wall is relatively thin, this region may not contribute greatly to LA ejection fraction. In turn, extensive ablation in this region may have little deleterious effect on regional and global LA functions. To test these hypotheses, regional LA function using cardiac magnetic resonance imaging (cMRI) and unique wall motion analysis methodology was measured in normal volunteers and was compared to similar measurements in patients before and after catheter ablation for paroxysmal or persistent AF.

2 Methods

2.1 Study population

All patients provided signed consent for the investigational protocol that was reviewed, approved, and overseen by the Human Investigation Committee of Beaumont Hospitals. Initial testing was performed in 12 healthy volunteers without a history of arrhythmia or other cardiac disease in order to define normal parameters. Subsequently, consecutive patients with AF scheduled to undergo a catheter-based AF ablation procedure were prospectively enrolled. Patients were imaged with cMRI prior to and again 3 months after the procedure. Patients with persistent AF were not cardioverted and underwent imaging during ongoing AF preprocedure. Patients who remained free of recurrent AF post ablation at the time of the follow-up scan, defined as freedom from recurrent AF symptoms and no documented AF on an autotrigger 30-day looping event recorder, were included. Patients with incomplete scans were excluded from this analysis. Seventy cMRI scans from the 12 normal patients, 16 patients with paroxysmal AF, and 13 patients with persistent AF comprised the study.

2.2 AF ablation procedure

All ablation patients underwent double transseptal catheterization under hemodynamic, fluoroscopic, and intracardiac echocardiographic (ICE) guidance. Two 8.5-Fr sheaths were placed in the left atrium and PVs. Mapping and catheter ablation was performed with a closed-tip irrigated catheter (Chilli II, Boston Scientific, Natick, MA, USA). LA catheter ablation was guided by ICE imaging using a 9-Fr 9-MHz mechanical transducer system (UltraICE, Boston Scientific, Natick, MA, USA) and electroanatomical navigation (NAVX System, St. Jude Medical, Minneapolis, MN, USA). Sequential radiofrequency (RF) lesions were created in an encircling pattern outside of the LA–PV junction for each pair of right and left veins. After completion of the encircling ablation line, the veins were mapped for the presence of pulmonary vein potentials (PVPs). If PVPs were still evident, additional ablations were performed at the sites of earliest PVP activation along the ablation line. After the elimination of all PVPs, high output pacing (>15 mA) was performed from at least three circumferential sites within the vein to confirm exit block. Complete PV isolation was defined as bidirectional conduction block of each of the PVs confirmed at least 20 min after the last ablation. In patients with a history of persistent AF or paroxysmal AF in the presence of structural heart disease, encircling PV isolation was supplemented with linear ablation and ablation of any areas revealing complex atrial fractionated electrograms. CAFEs were targeted in the LA and CS in the persistent population until all highly fractioned sites were ablated or until the rhythm terminated or organized to an atrial flutter. Sequential RF lesions were created in a linear pattern along the superior roof of the LA between the left and right superior PVs and from the left inferior PV to the mitral annulus. Completion of these ablation lines was confirmed by creation of double electrogram potentials along the ablation line [1, 2].

2.3 Image acquisition

cMRI was performed with a 1.5-T machine (Sonata, Siemens Medical Solutions USA, Malvern, PA, USA). Localizing scans were followed by breath-hold cine acquisitions, employing a previously described balanced steady-state free-precession electrocardiographically gated segmented k-space MRI pulse sequence [10, 11]. Retrogating and pulse sequence adjustment were employed to ensure that as much of end-diastole as possible was included in the sequence. Patients in AF obtained gated scans with arrhythmia rejection similar to the method reported by Therkelson [11]. Typical imaging parameters were as follows: TR ms/echo time ms of 3.0/1.5, flip angle of 55–80°, bandwidth of 930 Hz/pixel, one signal acquired, field of view of 325×400 mm, matrix of 206×256 (phase x frequency), interpolated, and in-plane resolution of 1.6×1.6 mm, averaging 20 phases and 16–24 segments. One midline vertical long axis (VLA) 6-mm slice image was obtained parallel to the axis going from the tip of the mitral valve to the apex of the left ventricle on the cinematographic four-chamber image at end-diastole. Horizontal

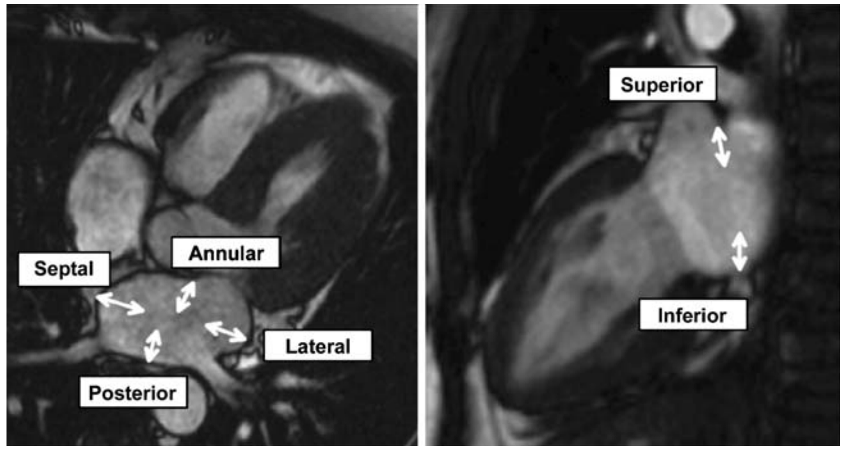


Fig. 1 Radial measurements. Regional wall motion in the *radial* dimension was measured from an arbitrary central reference point in the center of the left atrium to the midpoint of each of six segments

long axis (HLA) through the left atrium was planned perpendicular to the VLA image plane. Six to ten 6-mm slices with no interslice gaps were performed in the HLA plan spanning the atria. Similarly, six to ten short-axis slice images were obtained through the left atrium parallel to the mitral valve. The same sequence was used to visualize both ventricles with a stack of short-axis images and included ten to sixteen 6-mm slices with no interslice gaps.

2.4 Image analysis

Boundaries of the left atria and left ventricle were obtained in the each short-axis image. The LV and LA volumes were then determined by Simpson's rule. LA volume was also calculated by the biplane method as previously described. Atrial volumes were measured throughout the cardiac cycle. End-systolic and end-diastolic left ventricular volumes were recorded. Segmental wall motion was measured at each of the three phases with Siemens graphic tools. Regional LA wall motion was measured at each of the three phases with Siemens graphic tools. A horizontal slice that identified prespecified landmarks was used for analysis. Two methods to quantify regional wall motion were employed. Regional wall motion in the *radial* dimension was measured from an arbitrary central reference point in the center of the left atrium to the midpoint of each of six segments: the annular chord, posterior chord, the septal chord, and the lateral chord. Measurements of the superior and inferior chords were performed using a representative short-axis midcavity image and measurements from a central reference point to the atrial roof and to the atrial floor, respectively (Fig. 1). Measurements of *chordal* wall segment motion were made by identifying anatomical structures that could be observed throughout the cardiac cycle, then measuring the chordal distance between those structures in the three phases of the cardiac cycle. Measurements were made between the medial left PV–LA junction and the lateral right PV–LA junction (posterior chord), from the lateral left PV–LA junction to the lateral mitral valve annulus (MVA; lateral chord), from the septal right PV–LA junction to the septal MVA (septal chord), and from the lateral to septal MVA (annulus) (Fig. 2). Bland–Altman analysis of LA regional parameters measured by two blinded observers was performed in 12 studies. Bland–Altman analysis showed that the mean differences were randomly distributed within only one observation outside of the 2 standard deviations from the mean difference. Posterior chordal measurements displayed higher variability than other measurements due to the technical difficulty of defining the precise location of the PV–LA junction during the cardiac cycle and were removed from the final analysis. Other measurements were reproducible within 5%.

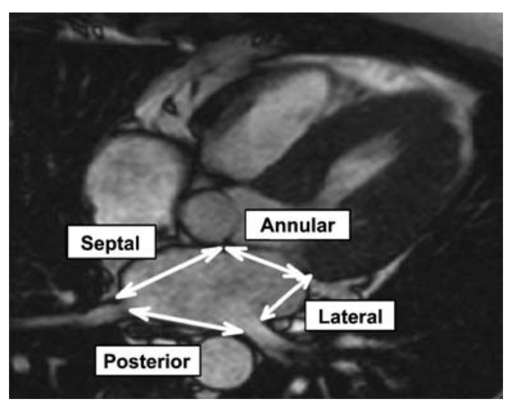


Fig. 2 Chordal measurements. Regional wall motion in the *chordal* dimension were made between the medial left PV–LA junction and the lateral right PV–LA junction (*posterior chord*), from the lateral left PV–LA junction to lateral MVA (*lateral chord*), from the septal right PV–LA junction to septal MVA (*septal chord*), and from lateral to septal MVA (*annulus*)

2.5 Parameters of LV and LA function

LV end-diastolic volume index and end-systolic volume index were derived from the volume–time curves for maximal and minimal values. LV stroke volume index and ejection fraction were subsequently computed. LA minimum (LA_{min}), LA maximum (LA_{max}), and LA pre-contractile (LA_{pre}) volumes indices were determined from the time–volume curves. Four relevant values, i.e., cyclic volume change index, LA stroke volume index, total LA percent emptying, and active LA percent emptying, were computed according to Jarvinen et al. [12]. Regional LA motion was analyzed during passive and active atrial emptying. Anterior, septal, and lateral chordal motion was recorded. Anterior, posterior, septal, lateral, superior, and inferior radial motion was recorded.

2.6 Statistical analysis

LA volumes, LA function, and regional atrial function were expressed as the mean±standard deviations. Interobserver and intraobserver variabilities of the LA global and regional functional measurements were assessed by Bland–Altman analysis. The interobserver and intraobserver mean differences with 95% confidence intervals were reported for all measured LA global and regional functional parameters. The comparisons of the parameters of global or regional atrial function before and after ablation were analyzed by a paired Student's *t* test analysis (two-tailed). Comparisons involving normal controls to AF patients were analyzed by unpaired Student's *t* tests (two-tailed).

3 Results

3.1 Patient characteristics

The baseline patient characteristics are displayed in Table 1. In addition to encircling PV isolation, linear atrial ablation was performed in 69% of patients with paroxysmal AF and 100% of patients with persistent AF. Patients with AF were older than the controls and had a higher prevalence of structural heart disease. Compared to paroxysmal AF patients, those with persistent AF were older, had more comorbidities, and had larger atrial dimensions at baseline.

3.2 Global atrial and ventricular function

Global LA and ventricular function is reported in Table 2. Baseline LA volume indices (maximum and minimum) were greater in the patients with AF than those of the healthy volunteers ($p<0.01$). Furthermore, the persistent AF subgroup had atrial volumes greater than that seen in the paroxysmal AF subgroup ($p<0.01$). LA transport as assessed by total percent emptying and cyclical change index were diminished in the persistent AF population ($p<0.01$) when compared to normal volunteers, but these values were only mildly depressed in the paroxysmal AF subgroup.

AF ablation was associated with a reduction in LA volumes in the paroxysmal AF and persistent AF populations compared to preablation measurements ($p<0.01$). Post ablation, the LA volumes in paroxysmal AF patients were comparable to those in the normal volunteer cohort ($p=$

Table 1 Baseline patient characteristics

	Paroxysmal AF (n=16)	Persistent AF (n=13)	Normal volunteers (n=12)
Age (years)	54±11	58±10	33±3
Male, *n* (%)	11 (69)	7 (54)	6 (50)
Weight (kg)	91±19	100±16	68±10
Body surface area	2.1±0.3	2.2±0.2	1.8±0.1
AF duration (years)	4.1±3.4	2.0±1.0	0
Number of failed antiarrhythmics	1.9±1.0	1.5±1.0	0
Hypertension, *n* (%)	6 (38)	8 (62)	0
Diabetes, *n* (%)	1 (6)	4 (38)	0
Coronary artery disease, *n* (%)	3 (19)	8 (62)	0
Valvular heart disease, *n* (%)	0	0	0
Chronic obstructive pulmonary disease, *n* (%)	0	2 (15)	0
Smoking, *n* (%)	0	0	0
Hyperlipidemia, *n* (%)	8 (50)	8 (62)	0
Baseline echocardiography data			
LV ejection fraction (%)	56.0±4.5	52.9±10	NA
LA size (mm)	39±5	44±7	NA

Table 2 Global LA function in paroxysmal AF, persistent AF, and normal volunteers

	Paroxysmal AF (n=16)			Persistent AF (n=13)			Normal volunteers (n=12)		
	Pre	Post	p value	Pre	Post	p value		p value (vs. baseline paroxysmal AF)	p value (vs. baseline persistent AF)
LA volume index									
Maximal (cc/m^2)	37.0±6.4	28.5±5.9	<0.01	41.4±8.7	36.7±10.0	0.05	28.8±6.1	<0.01	<0.01
Precontractile (cc/m^2)	26.9±5.5	20.0±5.5	0.02	NA	NA		18.5±5.7	<0.01	
Minimum (cc/m^2)	19.7±5.7	16.3±5.9	<0.01	31.7±9.3	24.0±8.8	<0.01	12.8±4.9	<0.01	<0.01
LA function									
Cyclical change (cc/m^2)	17.3±3.7	12.2±2.9	<0.01	9.7±4.4	12.7±5.0	0.04	16.0±4.2	0.40	<0.01
Total percent emptying	47.3±10.1	42.7±9.4	0.17	24.1±11.8	34.8±10.2	<0.01	55.6±12.8	0.08	<0.01
LA stroke volume (cc/m^2)	8.9±2.8	5.7±2.6	0.02	NA	NA		5.7±2.3	<0.01	
LA active percent emptying	33.4±8.3	26.2±7.9	0.08	NA	NA		31.3±10.5	0.74	
Left ventricular function									
LV end-diastolic volume (cc/m^2)	46.1±10.4	49.4±11.3	NS	46.2±9.1	47.0±10.1	NS	46±9.1	NS	NS
LV end-systolic volume (cc/m^2)	17.4±7.3	18.0±6.1	NS	19.1±6.9	16.8±6.5	NS	19.1±6.9	NS	NS
LV ejection fraction	63.3±10.7	64.2±6.7	NS	59.8±9.9	65.0±10.8	NS	59.8±9.9	NS	NS

NS), while persistent AF patients continued to demonstrate significant LA enlargement ($p<0.01$). Transport function as assessed by cyclical change and total percent emptying increased after ablation in the persistent AF population ($p<0.01$). After ablation in the paroxysmal AF group, significant reductions in the LA cyclical change ($p<0.01$) and active atrial stroke volume ($p=0.02$) and trends toward decreased total percent emptying ($p=0.17$) and active percent emptying ($p=0.08$) were observed (Figs. 3 and 4).

3.3 Regional LA function (preablation and post ablation)

Changes in regional wall motion with catheter ablation were analyzed by measuring radial fractional shortening and chordal fractional shortening. In the paroxysmal AF group, radial motion was diminished post ablation in the lateral LA ($p=0.02$). The remaining segments displayed similar radial motion after ablation. In the persistent AF population, radial motion significantly improved after catheter ablation in the anterior, septal, and inferior regions. The remaining segments showed a trend towards improved radial motion post ablation; however, these changes were not statistically significant (Fig. 5). The differences in chordal motion before and after ablation (Fig. 6) followed the same trends as were seen in the radial segment analysis; however, these changes did not achieve statistical significance.

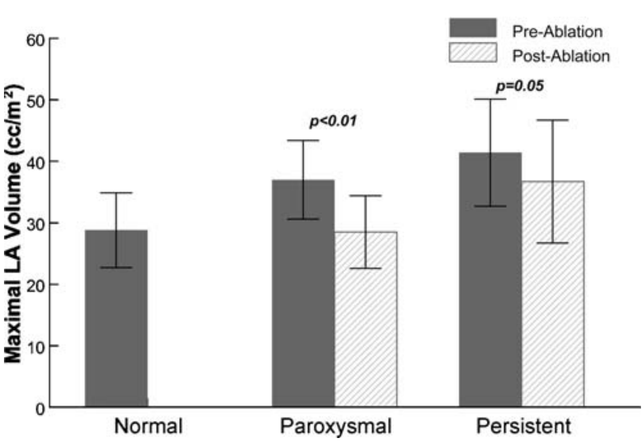


Fig. 3 Effect of ablation on maximum LA volume. Maximum LA volumes in normal volunteers and in paroxysmal and persistent AF patients preablation and post ablation

4 Discussion

Catheter and surgical ablation procedures are now widely performed to eliminate AF. The relative contributions of opposing effects of ablation, namely, improving atrial function by eliminating the arrhythmia and allowing positive electrical and anatomical remodeling vs. worsening LA contractility due to extensive destruction of contractile myocardium, have not been fully characterized. The present study compared baseline global and regional LA function of normal volunteers to that of patients with AF and evaluated the effects of PV isolation and linear ablation on global and regional LA functions. Patients with a history of paroxysmal AF had LA function similar to that of normal volunteers prior to ablation. However, these patients displayed a 15–25% decrease in global LA transport function parameters and evidence of impairment of regional

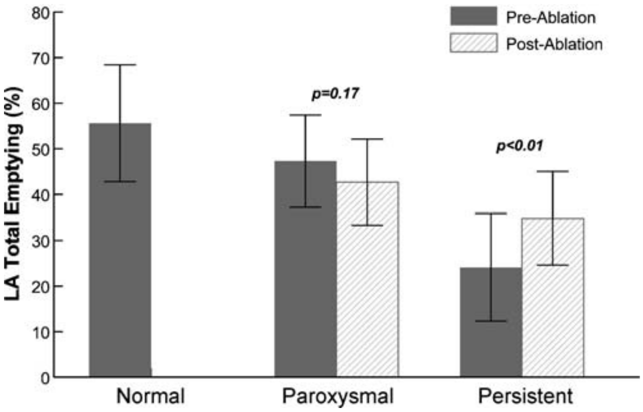


Fig. 4 Effect of ablation on LA transport. Total LA percent emptying in normal volunteers and in paroxysmal and persistent AF patients preablation and post ablation. LA percent emptying=[$(LA_{max})-(LA_{min})$]/(LA_{max})

motion after ablation. These results indicate that extensive ablation of the LA has a mild deleterious effect on LA contractility. In patients with persistent AF, baseline global and regional LA functions were significantly impaired compared to normal volunteers. This observation is consistent with the negative anatomical remodeling that has been previously reported in patients with AF [13, 14]. After catheter ablation and restoration of normal sinus rhythm, LA function significantly improved in the persistent AF population. Parameters of global LA function improved approximately 20–30% while regional motion appeared to improve in all segments. In the persistent AF population, therefore, it appears that the benefits of rhythm restoration and positive remodeling offset the loss of contractility associated with extensive ablation of LA myocardium. As anticipated, despite restoration of sinus rhythm with ablation, the LA function in the persistent AF subgroup remained far below that of normal volunteers.

4.1 Previous studies

4.1.1 LA volume

Therkelsen reported similar LA reduction in patients with persistent or permanent AF after successful cardioversion with serial cardiac MRI studies [11]. From this study and many others, it is apparent that termination of AF results in positive remodeling with resultant decreases in atrial volumes, increases with LA emptying fraction, and increasing in “a” wave velocities [15, 16]. However, four prior studies designed to evaluate LA volume post ablation reported decreases in maximum and minimum LA volumes from 10% to 20% [6, 7, 9, 17]. This correlates well with our study that found decreases in LA volumes of approximately 15–25%. This decrease was seen in patients with paroxysmal AF and persistent AF. The decreases of atrial volume post ablation in the persistent AF group may be explained in part by the positive remodeling effect; however, it is less likely that this can explain the volume decrease seen in the paroxysmal AF subgroup. Our study exhibits decreases in global LA transport function and evidence of regional dysfunction in areas that ablation is known to occur in the

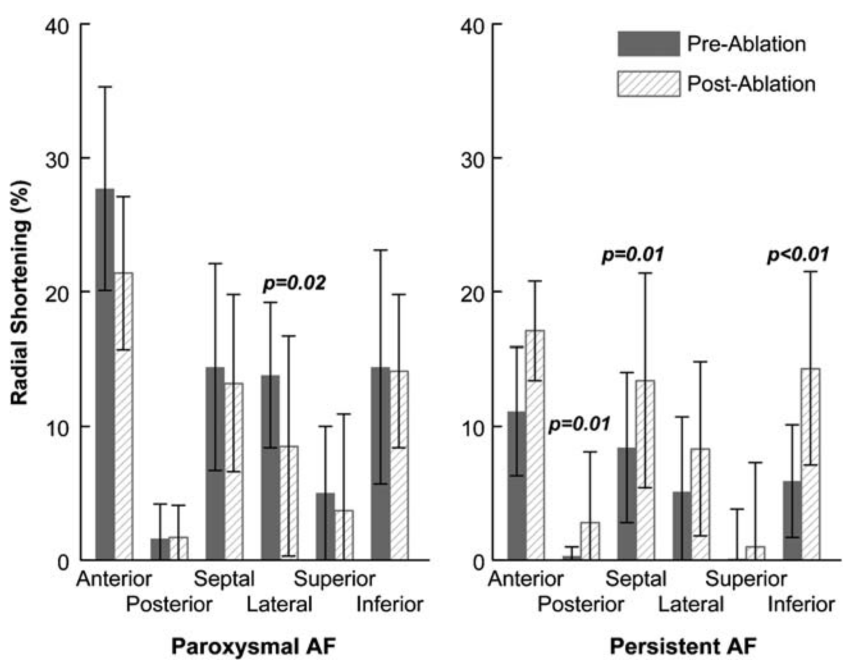
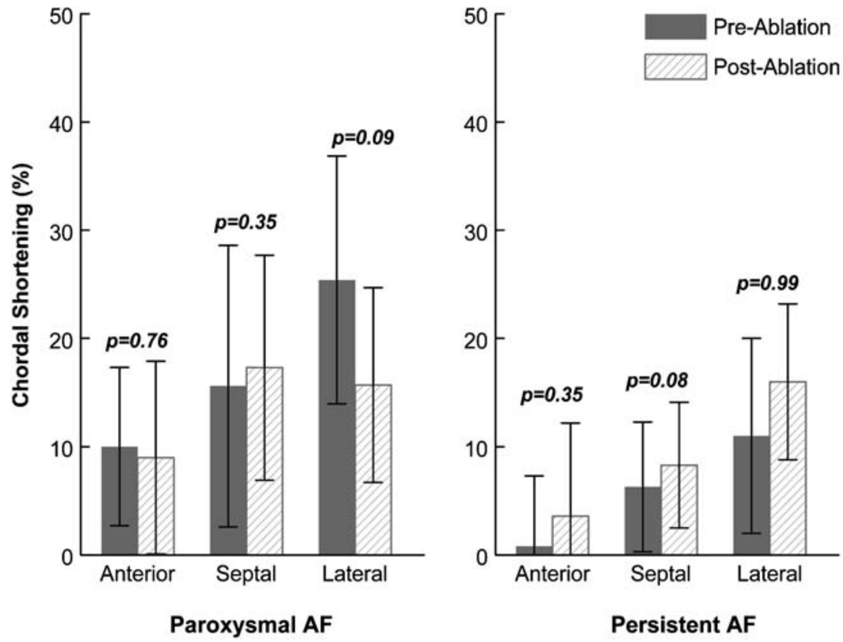


Fig. 5 Effect of ablation on regional LA motion (radial). Regional wall motion in the *radial* dimension preablation and post ablation in paroxysmal AF patients and in persistent AF patients

Fig. 6 Effect of ablation on regional LA motion (chordal). Chordal regional wall motion preablation and post ablation in paroxysmal AF patients and in persistent AF patients



paroxysmal AF subgroup. These adverse changes would not be expected if positive remodeling was the dominant reason for reduction in atrial volumes. Therefore, the decreased volume seen in the paroxysmal AF subgroup is likely due to atrial scarring and tissue contraction. In the study by Hauser, LA scar burden was highly correlated with decreased LA active transport [17].

4.1.2 LA function

Multiple studies have evaluated the effects catheter and surgical AF ablation procedures have on LA function. Similar to our data, Oral and Hauser reported that PV isolation caused a decrease in LA EF of approximately 30% and 14% in the cohort of AF patients, which is similar to the 10–20% decrease in our paroxysmal AF population [9, 17]. In a controlled animal model evaluating the effects linear ablation has on LA in persistent AF and sinus rhythm, the findings parallel our findings. Ablation appeared to cause volume decrease and impairment in LA transport in the normal cohort similar to our paroxysmal AF population. In the dogs in persistent AF, LA size decreased and LA transport function improved from baseline; however, LA size and function never returned to that seen in a normal cohort which was seen in our persistent AF population [8].

Natale et al. evaluated the effects PVAI had in an AF population using echo and EBCT and noted overall improvement in LA EF and A wave velocity. The improvement seen in the persistent AF population is comparable to the improvement reported in this study [7]. The decreases in atrial function in the paroxysmal subgroup noted in our study and in the study of Oral were not reproduced by Natele. The patient population demographics seem relatively similar in each study. Interestingly, additional linear ablation lines were routinely done in studies where dysfunction was seen and were not done in the Natele study population. Routine linear ablation of the superior roof and mitral annulus may account for the dysfunction seen in the paroxysmal AF population. Relatively small amounts of posterior and superior regional motion are seen in a normal left atrium. It is conceivable that antral ablation limits tissue damage to regions that do not significantly contribute to overall LA function.

4.1.3 Regional LA motion/function

No gold standard regarding regional LA function exists. Recently, echocardiographic strain rate imaging and local tissue velocity in various LA regions have been reported, and in the future, the techniques may prove to be useful to evaluate the effects of ablation [18]. Three-dimensional echocardiography was shown to give reproducible LA volume measurements with excellent visualization of LA throughout the cardiac cycle [19]. A post surgical MAZE study used CT to assess regional LA motion in multiple segments of a horizontal slice slightly superior to MVA and reported worse wall motion the MAZE cohort compared to a control population. We feel that using this method to assess the effect catheter ablation has on LA function would be inadequate because the majority of the antral lesions occur more posterior to the plane chosen for analysis [20]. We chose cMRI to analyze regional LA function due to its ability to visualize all segments of the atrial wall during the cardiac cycle and its inherent ability to compensate for irregular heart rhythm [11]. Our study is the first to analyze *global and regional* atrial motion before and after ablation.

4.2 Limitations

Regional atrial wall function would optimally be assessed by myocardial tagging; however, the atrial wall is too thin for such software. Therefore, we employed radial and chordal measurements in a systematic way to assess regional function. Radial motion measurements would not be able to differentiate inward radial motion from those changes in wall position which occur with plane shift. Chordal measurements are dependent on accurate identification of fixed landmarks which can be difficult with various atrial anatomies and any variance from acquisition protocol. MR images are currently not interactive and accurate images and planes are dependent on appropriate acquisition. Despite these limitations, we feel that our regional measurements are reproducible and provide a good assessment of motion in six regions of the left atrium.

This is a single-center, unblinded analysis and subject to inherent bias associated with such an analysis. However, studies were independently reviewed by a second blinded reader and showed good correlation without evidence of systematic difference between the two sets of measurements to validate all findings. The control group consisted of a younger healthier population and differences between this group and the study cohort may be secondary to differences other than a history of AF. The changes observed in the persistent AF group after ablation may be due to the restoration of sinus rhythm, due to the effects of catheter ablation, or a combination thereof. Due to the small numbers of patients, the clinical significance of the diminished LA transport function remains unknown.

5 Conclusions

Maintenance of sinus rhythm and a reduction in AF burden clearly results in improvement in LA function. By analyzing a population with relatively less AF burden, this study also revealed that mild adverse effects on LA function do occur when aggressive ablation is performed. The presence of mild deleterious effects of tissue ablation intuitively makes sense; however, it is unclear if this results in any adverse clinical outcomes. Whether or not the regional changes seen have any impact on AF recurrence or thromboembolic risk remains to be determined.

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