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Reverse Left Atrial Remodeling After Balloon Mitral Valvuloplasty in Severe Rheumatic Mitral Stenosis: A Cardiac Magnetic Resonance Study

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Abstract

Background

Rheumatic mitral stenosis (MS) leads to chronic left atrial (LA) pressure overload, resulting in atrial enlargement and progressive impairment of reservoir, conduit, and contractile function. Although balloon mitral valvuloplasty (BMV) effectively relieves valvular obstruction, the extent of subsequent LA reverse remodeling remains incompletely defined. We aimed to evaluate changes in LA structure and phasic function after successful BMV using cardiac magnetic resonance (CMR).

Results

Forty-nine patients with isolated severe rheumatic MS underwent CMR before and 9–12 months after successful BMV, defined as a post-procedural mitral valve area ≥ 1.5 cm² without more than mild mitral regurgitation. Age- and sex-matched healthy individuals served as controls. At baseline, patients demonstrated significant LA enlargement and marked impairment of volumetric and deformation-derived reservoir, conduit, and contractile function compared with controls. Following BMV, indexed LA volumes decreased significantly, with parallel improvement in all phasic functional components. Recovery was most pronounced in LA reservoir and contractile strain indices, which approached normal values. In contrast, LA volumes and volumetric functional parameters remained significantly abnormal relative to controls.

Conclusion

Successful BMV was associated with meaningful but incomplete LA reverse remodeling within the first year after intervention. Functional recovery may precede full structural normalization after relief of chronic atrial pressure overload. CMR assessment of LA remodeling may provide clinically relevant insight into cardiac recovery and longitudinal follow-up after BMV in patients with rheumatic MS.

Introduction

Mitral stenosis (MS), most commonly of rheumatic etiology, is characterized by chronic obstruction to left ventricular inflow, leading to sustained elevation of left atrial (LA) pressure and progressive impairment of atrial structure and function.[1] Long-standing pressure overload results in LA dilatation, wall fibrosis, reduced compliance, and deterioration of phasic atrial functions, including reservoir, conduit, and contractile components.[2] [3] These changes are closely linked to adverse clinical outcomes such as atrial fibrillation, thromboembolic events, and heart failure, making assessment of LA remodeling an important marker of disease severity and clinical risk in MS.[4] [5]

Balloon mitral valvuloplasty (BMV) is the treatment of choice for patients with symptomatic severe rheumatic mitral stenosis (MS) and favorable valve morphology, providing immediate relief of transmitral obstruction and reduction of left atrial (LA) pressure.[6] Previous studies have demonstrated reductions in LA dimensions and volumes following successful BMV, predominantly using two-dimensional and three-dimensional echocardiography, with most investigations limited to immediate or short-term follow-up. [7] [8] However, LA volumetric parameters are highly load dependent and may not fully capture intrinsic myocardial recovery, particularly in the mid- to long-term period after intervention.[9]

Cardiovascular magnetic resonance (CMR) is considered the gold standard for the assessment of cardiac chamber volumes due to its high spatial resolution and excellent reproducibility, allowing accurate quantification of LA size and remodeling.[10] Furthermore, CMR feature tracking (FT) applied to routine cine images enables comprehensive evaluation of LA phasic deformation, providing load-independent insights into atrial myocardial function.[11] Despite its potential advantages, data on CMR-derived LA volumetric and deformation changes following BMV remain limited. The aim of this study was to assess mid-term changes in left atrial structure and phasic function following successful balloon mitral valvuloplasty using CMR-derived volumetric and deformation parameters, and to compare these findings with healthy controls. Secondary objectives included evaluating the relationship between mitral stenosis severity and LA functional indices.

Methods

Study Design and Population

This observational cohort study was conducted at Aswan Heart Centre, a tertiary care referral center in Upper Egypt. Between December 2017 and December 2022, 68 consecutive patients with symptomatic severe rheumatic mitral stenosis were screened for inclusion. In addition, 30 age- and sex-matched healthy individuals without known cardiovascular disease were prospectively recruited as a control group.

Patients were eligible for inclusion if they had symptomatic rheumatic mitral stenosis in sinus rhythm, a mitral valve area (MVA) < 1.5 cm², and favorable valve morphology based on standard echocardiographic scoring systems, and subsequently underwent balloon mitral valvuloplasty (BMV). Successful BMV was defined as achievement of a post-procedural MVA ≥ 1.5 cm² in the absence of more than mild mitral regurgitation.

Exclusion criteria included inadequate post-procedural valve dilation (MVA < 1.5 cm²), development of moderate or severe mitral regurgitation, atrial fibrillation at baseline or during follow-up, prior cardiac surgery, uncontrolled systemic hypertension, advanced systemic disease, or any condition known to independently affect left atrial function.

Imaging Protocol

CMR Protocol

Image Acquisition

Cardiovascular magnetic resonance imaging was performed using a 1.5-T scanner (Magnetom Aera, Siemens Medical Systems, Erlangen, Germany) with retrospective electrocardiographic gating. All images were acquired during breath-holding using balanced steady-state free precession (bSSFP) sequences.

Standard cine images were obtained in vertical long-axis two- and four-chamber views and in contiguous short-axis planes covering both ventricles from the base to the apex (12–14 slices).Typical imaging parameters included a flip angle of 50–70°, slice thickness of 6–8 mm with no interslice gap, matrix size of 160 × 256, field of view of 350–400 mm, repetition time of 3.2–3.8 ms, echo time of 1.6–1.9 ms, and a temporal resolution of approximately 25 ms.

CMR Image Analysis

All CMR datasets were analyzed using dedicated post-processing software by experienced observers blinded to clinical and echocardiographic data.

Left Atrial Volumetric Analysis

Left atrial (LA) volumes were quantified using the biplane area–length method from two- and four-chamber cine images. (Figs. 1 and 2). Semi-automated tracing of the LA endocardial borders was performed at different phases of the cardiac cycle, including the left atrial appendage while excluding pulmonary veins.

LA volume was calculated using the formula:

LA volume (mL) = 0.85 × A2C × A4C / L,[12]

where A2C and A4C represent the LA areas in the two- and four-chamber views, respectively, and L is the shorter long-axis LA length measured from the atrial roof to the midpoint of the mitral annulus.[12]

LA volumes were measured at:

- **Maximum LA volume (LA Vmax)**: at left ventricular end-systole
- **Pre-atrial contraction volume (LA Vpre-A)**: at late LV diastole immediately before atrial contraction
- **Minimum LA volume (LA Vmin)**: at LV end-diastole following atrial contraction

All volumes were indexed to BSA. LA size assessment was therefore based on two-dimensional measurements rather than three-dimensional volumetric acquisition, a limitation acknowledged in the interpretation of results.

Volumetric indices of LA phasic function were calculated as follows:

• Total (reservoir) emptying fraction:

- (LAVmax − LAVmin) / LAVmax × 100

• Passive (conduit) emptying fraction:

- (LAVmax − LAVpre-A) / LAVmax × 100

• Active (booster pump) emptying fraction:

- (LAVpre-A − LAVmin) / LAVpre-A × 100

Figure (1)

LA tracing in 4 and 2 chamber views. LA length is taken as the shorter long axis length (From atrial surface to midpoint of mitral annular plane). Control subject no. 4

Figure (2)

Left atrial tracking in the 4-chamber view in a patient with severe rheumatic mitral stenosis (Study Patient no. 22)

Left Atrial Feature-Tracking Analysis

LA strain and strain-rate parameters were derived from bSSFP cine images using feature-tracking software (MASS MR Analytical Software System, version 2021-EXP, Leiden University Medical Center, the Netherlands). Images were exported in DICOM format for offline analysis.

LA endocardial borders were manually delineated on two- and four-chamber cine images at LV end-systole and end-diastole. Manual adjustments were performed when necessary to ensure optimal tracking and to exclude pulmonary veins. Following application of the automated tracking algorithm, contours were propagated throughout the cardiac cycle. (Fig. 3). Tracking quality was visually inspected on a segmental basis.

Figure (3)

CMR LA Feature tracking. The figure shows a representative example of LA tracking in the 4 chamber view in control subject no. 4

Global LA deformation parameters were calculated by averaging values from six atrial segments. (Figs. 4, 5). The following strain components were analyzed:

- **Reservoir strain (εR)**: reflecting LA reservoir function during ventricular systole
- **Conduit strain (εCD)**: reflecting passive LA emptying during early ventricular diastole
- **Contractile strain (εCT)**: reflecting active LA booster pump function during late ventricular diastole

Corresponding strain-rate parameters included:

- **SRs**: peak positive strain rate (reservoir function)
- **SRe**: peak early negative strain rate (conduit function)
- **SRa**: peak late negative strain rate (contractile function)

Figure (4)

Strain curves for the six segments of LA (Left). Average strain curve for all segments (Right). Control subject no. 4

Figure (5)

LA strain and strain rate profiles (Control subject no. 4)

LA functions were assessed from volumetric and strain indices (Fig. 6)

Figure (6)

The 3 phasic functions of LA as assessed by volumetric and strain indices

Echocardiographic Assessment of Mitral Stenosis

All patients underwent comprehensive evaluation of mitral stenosis severity at baseline and follow-up according to current guideline recommendations. Transthoracic echocardiography (TTE) was performed using commercially available ultrasound systems with patients in the left lateral decubitus position. Standard parasternal long- and short-axis, apical two-, three-, and four-chamber views were acquired.

Mitral valve area (MVA) was primarily assessed by direct planimetry in the parasternal short-axis view at the level of the leaflet tips during mid-diastole, ensuring optimal image quality and avoidance of oblique cuts. Pressure half-time (PHT)–derived MVA was calculated when appropriate but was not used as the primary measure, particularly in the post-BMV setting, due to its known limitations following changes in left atrial and left ventricular compliance.

Transmitral inflow velocities were obtained using pulsed-wave Doppler from the apical four-chamber view, with the sample volume positioned at the tips of the mitral leaflets. Continuous-wave Doppler was used to record the highest transmitral velocities, and the mean diastolic transmitral gradient (MG) was calculated by tracing the diastolic velocity–time integral. All Doppler measurements were averaged over three consecutive cardiac cycles in patients in sinus rhythm.

Mitral regurgitation severity was assessed using an integrative approach incorporating color Doppler jet characteristics, vena contracta width, and spectral Doppler findings, in accordance with guideline recommendations. Right ventricular systolic pressure was estimated from the peak tricuspid regurgitation velocity using the modified Bernoulli equation, with right atrial pressure estimated from inferior vena cava size and collapsibility.

Statistical Analysis

Statistical analyses were performed using SPSS software (version 28.0; IBM Corp., Armonk, NY). Continuous variables were tested for normality using the Kolmogorov–Smirnov and Shapiro–Wilk tests and were found to be non-normally distributed. Accordingly, continuous data are presented as median with interquartile range (IQR), and categorical variables are expressed as frequencies and percentages.

Comparisons between patients with mitral stenosis and healthy controls were performed using the Mann–Whitney U test. Paired comparisons within the patient group before and after balloon mitral valvuloplasty were conducted using the Wilcoxon signed-rank test. The strength and direction of associations between continuous variables were assessed using Spearman rank correlation analysis, with correlation coefficients reported as Spearman's rho (ρ).

All statistical tests were two-sided, and a p-value < 0.05 was considered statistically significant.

Results

We screened 68 consecutive patients, nineteen patients were excluded for various reasons as mentioned in Figure (7). Our final cohort was 49 patients for whom CMR study was done at baseline (pre BMV) and after mid-long term follow up (9-12 months). CMR was also done for thirty age and sex matched healthy volunteers as a control group. We categorized patients and controls into 3 groups; Group A (Pre BMV), Group B (Post BMV) and Group C (Controls)

Baseline Characteristics

Baseline characteristics are shown in table (1). The median age of the MS patients was 31 years with a marked female predominance (84%). Most patients were highly symptomatic at presentation, with about 70% of patients in NYHA class III (Median NYHA class =3) and a median symptom duration of 12 months. Baseline demographics and hemodynamic parameters were comparable to healthy controls.

Table 1. Baseline Clinical Characteristics of Study Patients

Parameter	MS patients	Control group	p-value
Age (years)	31 (+/-9.5)	30 (+/-8)	0.40
Male sex, n (%)	8 (16)	10 (33.3)	0.08
Female sex, n (%)	41 (84)	20 (66.7)	—
Median NYHA class	3	—	—
Duration of symptoms (months)	12 (18)	—	—
Previous thromboembolism, n (%)	4 (8.2)	0	—
Previous BMV, n (%)	6 (12.2)	0	—
Diabetes mellitus, n (%)	0	0	—
Hypertension, n (%)	0	0	—
BSA (m^2)	1.7 (0.2)	1.7 (0.2)	0.21
SBP (mmHg)	116 (13.5)	115 (9.4)	0.80
DBP (mmHg)	75 (16)	70 (9)	0.19
HR (beats/min)	74 (21)	72 (18)	0.82

Values are expressed as median (interquartile range). Abbreviations: BMV, balloon mitral valvuloplasty; BSA, body surface area; DBP, diastolic blood pressure; HR, heart rate; NYHA, New York Heart Association; MS, mitral stenosis; SBP, systolic blood pressure.

Procedural Results and Hemodynamic Effect of Balloon Mitral Valvuloplasty

Most patients reported significant functional improvement following balloon mitral valvuloplasty, with the median NYHA class improving from 3 to 1 at follow-up. Balloon mitral valvuloplasty resulted in a marked and immediate improvement in mitral valve hemodynamics. Mitral valve area increased from a median of 0.9 cm^2 to 1.8 cm^2 ($p<0.001$), accompanied by a significant reduction in mean transmitral gradient from 13 mmHg to 5 mmHg ($p<0.001$). Peak transmitral gradient decreased from 22 mmHg to 11 mmHg ($p<0.001$). The left ventricular ejection fraction remained unchanged (65% vs. 66%). There was a trend toward lower pulmonary artery systolic pressure (from 45 mmHg to 40 mmHg, $p= 0.08$) in the immediate postoperative echocardiogram. (Table 2)

Table 2 . Baseline Routine Echocardiographic Data of MS Patients

Parameter	Pre-BMV	Immediately post-BMV	p-value
Mitral valve area by planimetry (cm²)	0.9 (0.2)	1.8 (0.3)	<0.001
Peak transmitral gradient (mmHg)	22 (11.8)	11 (8)	<0.001
Mean transmitral gradient (mmHg)	13 (6.5)	5 (4.1)	<0.001
Left ventricular ejection fraction (%)	65 (7)	66 (8)	0.97
Estimated PASP (mmHg)	45 (20)	40 (16)	0.08

Values are expressed as median (interquartile range). Abbreviations: BMV, balloon mitral valvuloplasty; PASP, pulmonary artery systolic pressure.

Left Atrial Volumetric Remodeling

At baseline, cardiac magnetic resonance imaging demonstrated marked left atrial structural and functional remodeling in patients with mitral stenosis compared with healthy controls (table 3). All indexed left atrial volumes were significantly increased, reflecting chronic pressure overload with impaired atrial emptying. In parallel, left atrial volumetric indices of LA function were globally impaired, with significant reductions in reservoir and pump functions, indicating compromised atrial compliance, abnormal atrial–ventricular coupling, and reduced contractile function. Regarding Conduit function, there was improvement of the passive emptying index (p<0.001) but the change in conduit volume was not statistically different among both groups.

Table 3 . Baseline CMR-derived Left Atrial volumes and Functional indices

Parameter	**MS patients (n=49)**	**Controls (n=30)**	**p-value**
LA indexed volumes (mL/m²)			
Vmax	74.5 (29.7)	32.4 (6.3)	<0.001
Vmin	55.2 (23.6)	11.8 (4.3)	<0.001
Vpre-atrial contraction	68.1 (26.7)	18.2 (4.7)	<0.001
LA functional parameters			
Expansion index (%)	30.7 (17.7)	182.9 (69)	<0.001
LA ejection fraction (%)	23.4 (10.2)	64.7 (8.5)	<0.001
Passive emptying index (%)	8 (8.4)	46.4 (12.7)	<0.001
Conduit volume (mL/m²)	25.6 (10.5)	22.4 (6.8)	0.13
Active emptying index (%)	17.5 (8.6)	36.3 (12.8)	<0.001

Values are presented as median (IQR). p-values indicate comparison between MS patients and controls. Abbreviations: MS, mitral stenosis; LA, left atrium; Vmax, maximal LA volume; Vmin, minimal LA volume; Vpre-atrial contraction, LA volume before atrial contraction.

Following successful balloon mitral valvuloplasty, there was a significant reduction in left atrial volumes, accompanied by a marked improvement in left atrial volumetric functional indices of reservoir, conduit, and pump function. Despite these improvements, post-procedural volumetric indices did not fully normalize when compared with healthy controls. (Table 4)

Table 4 . CMR-Derived Left Atrial Indexed Volumes Before and After Balloon Mitral Valvuloplasty

Parameter	Group A (Pre-BMV)	Group B (Post-BMV)	Median Difference (A–B) (95% CI)	p-value (A vs B)	Group C (Controls)	p-value (B vs C)
LA indexed volumes (mL/m²)						
V max	74.5 (29.7)	61.9 (19.6)	−13.5	<0.001	32.4 (6.3)	<0.001
V min	55.2 (23.6)	34.9 (19.9)	−21.3	<0.001	11.8 (4.3)	<0.001
V pre-A	68.1 (26.7)	50.2 (19.8)	−19.2	<0.001	18.2 (4.7)	<0.001
Expansion index (%)	30.7 (17.7)	78.7 (44.6)	42.3	<0.001	182.9 (69)	<0.001
LA ejection fraction (%)	23.4 (10.2)	44 (14.7)	17.4	<0.001	64.7 (8.5)	<0.001
Passive emptying index (%)	8 (8.4)	17.4 (15.3)	11	<0.001	46.4 (12.7)	<0.001
Conduit volume (mL/m²)	25.6 (10.5)	24.2 (11.9)	-0.1	0.94	22.4 (6.8)	0.47
Active emptying index (%)	17.5 (8.6)	27.6 (15.4)	10.9	<0.001	36.3 (12.8)	0.002

Left Atrial Strain Parameters

Deformation analysis using CMR strain imaging demonstrated severe baseline impairment of all left atrial (LA) strain parameters including reservoir, conduit, and active strain in patients with severe mitral stenosis compared to healthy controls. (all $p < 0.001$ vs. controls).

Following successful balloon mitral valvuloplasty (BMV), significant improvements were observed across all LA strain parameters at 9–12 months follow-up (all $p < 0.001$ vs. pre-BMV). LA reservoir strain improved substantially, reaching levels comparable to healthy controls ($p = 0.69$), suggesting restoration

of atrial compliance and reservoir function. Active (contractile) strain also improved significantly (p = 0.05), reflecting enhanced atrial contribution to ventricular filling post-intervention. (Table 5 and Figure 8)

In contrast, despite improvement of conduit strain and SR after BMV, both remained significantly lower than in controls (both p < 0.001), indicating the incomplete recovery of LA conduit function despite effective relief of mitral stenosis.

Table 5 . Left Atrial Strain and Strain Rates Across the Three Groups

Parameter	Group A Pre-BMV	Group B Post-BMV	Median difference (95% CI)	p-value (A vs B)	Controls	P-value (B vs C)
Reservoir strain (%)	10.4 (7.8)	18.1 (8.2)	6.23	<0.001	18 (9.1)	0.69
SRs (s^{-1})	49.2 (36.2)	70.7 (36.5)	23	<0.001	75.2 (26.4)	0.68
Passive strain (%)	4.1 (3.4)	7.6 (5.4)	3.7	<0.001	11.9 (5.9)	<0.001
SRe (s^{-1})	-24.5 (19.9)	-38.4 (29.2)	17.7	<0.001	-94.2 (53.2)	<0.001
Active strain (%)	4.7 (4.6)	7.1 (4.9)	2.1	<0.001	8.8 (2)	0.05
SRa (s^{-1})	-39.2 (40.7)	-58.3 (56.6)	17.3	0.002	-61.5 (20.1)	0.29

Values are expressed as median (interquartile range). Abbreviations: BMV, balloon mitral valvuloplasty; SR, strain rate; SRs reservoir strain rate; SRe passive strain rate; SRa active strain rate.

Correlation analysis

At Baseline prior to BMV, a higher mean gradient (MG) across mitral valve in patients with severe MS was associated with higher EPASP (ρ= 0.5, p<0.001), worse passive strain (ρ=-0.4, p= 0.002) and passive SR (ρ=-0.3, p=0.02). Similarly, a smaller MVA by planimetry was associated with worse passive strain (ρ=0.3, p=0.01) and passive SR (ρ=0.4, p=0.005). The correlation between degree of mitral stenosis by both MVA and MG with LA reservoir strain among patients with severe MS was weak and not statistically significant. Following BMV, drop in MG from baseline (Δ MG) was correlated with the decrease in LA indexed V min (ρ=0.3, p= 0.038), improvement in LA expansion index (ρ=-0.4, p=0.003) and improvement in LA EF (ρ=-0.5, p=0.001). However, Δ MG was not significantly correlated with delta changes in LA indexed V max and PreA volumes. Δ MG was also significantly correlated with improvement of LA global strain (ρ=-0.5, p<0.001) and active LA strain (ρ=-0.5, p<0.001). (Figure 9)

Discussion

Left atrial (LA) function is increasingly recognized as a critical determinant of morbidity in mitral stenosis, as impairment of phasic atrial mechanics predisposes patients to atrial fibrillation and contributes to progressive functional limitation. [13] [14] Accurate and reproducible assessment of LA function is therefore essential. Cardiovascular magnetic resonance (CMR) offers important advantages over echocardiography in this setting, providing highly reproducible measurements of atrial volumes and phasic function that are less dependent on acoustic window limitations and geometric assumptions. This is particularly relevant in mitral stenosis, where the left atrium is often markedly enlarged and asymmetric, which may lead to underestimation of LA size and function by two-dimensional echocardiography. [15] Furthermore, CMR feature-tracking enables robust quantification of atrial strain with high spatial resolution and favourable signal-to-noise characteristics, and is less susceptible to image dropouts and tracking artifacts that commonly limit speckle-tracking echocardiography in dilated atria.[11] [16] [17] To our knowledge, this study is among the first to comprehensively characterize mid-term changes in LA volumetric and deformation parameters using CMR following BMV in rheumatic MS.

The concept of reverse LA remodeling following relief of mitral stenosis has been described in prior echocardiographic and CMR studies.[7] [18] [19] Consistent with these reports, we observed significant improvement in all phasic LA volumes, including maximal, pre-atrial contraction, and minimal volumes, following balloon mitral valvuloplasty (BMV). However, despite these favourable changes, LA volumes did not fully normalize compared with healthy controls. This incomplete recovery may reflect chronic atrial remodeling, fibrosis, and underlying atrial myopathy resulting from prolonged pressure overload. In addition, reverse remodeling may evolve over months to years, and the possibility of continued structural improvement beyond the follow-up period cannot be excluded.

Notably, the degree of transmitral gradient reduction was more strongly associated with the reduction in LA minimal volume than with other volumetric indices. Prior studies have demonstrated that LA minimal volume is sensitive to elevated left ventricular filling pressures. [20] [21] Accordingly, in patients with severe mitral stenosis—who experience a comparable state of chronic atrial pressure overload—effective reduction in atrial afterload following BMV may preferentially translate into a decrease in LA minimal volume, making it a sensitive marker of early hemodynamic improvement.

We also observed differential recovery of LA phasic function in response to unloading after BMV. LA reservoir function demonstrated the most pronounced and consistent improvement, with near-complete normalization of reservoir strain. This finding underscores the load-dependent nature of reservoir function, which primarily reflects atrial compliance and the ability of the left atrium to accommodate pulmonary venous return during ventricular systole. In contrast, LA conduit function remained persistently impaired, as evidenced by subnormal passive strain and early diastolic strain rate, despite successful relief of valvular obstruction. Conduit function appears to be influenced by left ventricular relaxation and intrinsic atrial myocardial properties, which may not substantially improve following BMV. [22] [23]

Active (contractile) LA function also improved after BMV but did not uniformly normalize, indicating only partial recovery of atrial contractile reserve. Rheumatic heart disease is known to involve atrial myocardium directly,[24] and persistent atrial fibrosis from rheumatic involvement may limit full restoration of contractile performance even after hemodynamic unloading. Consistent with this concept, we found that the degree of transmitral gradient reduction was significantly correlated with improvement in LA reservoir and active strain, highlighting the strong load dependence of these components of atrial function, while conduit function remained relatively independent of gradient reduction.

These findings suggest that comprehensive CMR assessment of LA function may provide incremental insights into atrial remodeling and recovery beyond conventional echocardiographic parameters in patients undergoing BMV.

Limitations

Our study has several limitations. First, the study population was limited to patients with severe rheumatic mitral stenosis, and the findings may not be generalizable to patients with calcific mitral stenosis or other aetiologies. Second, the study design did not include immediate post-procedural CMR assessment or extended long-term follow-up beyond 9–12 months; therefore, early changes and longer-term evolution of left atrial reverse remodeling could not be fully characterized. Third, left atrial size was assessed using two-dimensional biplane area–length measurements rather than three-dimensional volumetric techniques, which may have resulted in underestimation of true atrial volumes. Finally, although CMR-derived atrial strain provides detailed characterization of atrial mechanics, its broader clinical implementation remains limited by cost, availability, and lack of standardization across vendor platforms.

Conclusion

Successful balloon mitral valvuloplasty is associated with reverse remodeling of the left atrium, with significant improvement in left atrial structural and functional indices at mid-term follow-up. However, left atrial volumes did not fully normalize, suggesting the presence of partially irreversible atrial remodeling related to chronic pressure overload. Among atrial functional components, reservoir function demonstrated the most pronounced recovery, with near-complete normalization after BMV, whereas conduit function remained impaired despite effective gradient reduction. Improvement in transmitral gradient was significantly associated with recovery of reservoir and contractile strain, but not conduit strain, highlighting differential responsiveness of atrial functional components to hemodynamic unloading. Further studies with longer follow-up are warranted to determine the extent and durability of atrial reverse remodeling beyond one year.

Abbreviations

BMV

Balloon Mitral Valvuloplasty
BSA
Body Surface Area
bSSFP
Balanced Steady–State Free Precession
CI
Confidence Interval
CMR
Cardiac Magnetic Resonance
DBP
Diastolic Blood Pressure
EF
Ejection Fraction
EPASP
Estimated Pulmonary Artery Systolic Pressure
FT
Feature Tracking
HR
Heart Rate
IQR
Interquartile Range
LA
Left Atrium
LAV
Left Atrial Volume
LV
Left Ventricle
MG
Mean Gradient
MR
Mitral Regurgitation
MS
Mitral Stenosis
MVA
Mitral Valve Area
NYHA
New York Heart Association
PHT
Pressure Half–Time
SBP

Systolic Blood Pressure
SR
Strain Rate
SRa
Late Negative Strain Rate (Contractile)
SRe
Early Negative Strain Rate (Conduit)
SRs
Positive Strain Rate (Reservoir)
TTE
Transthoracic Echocardiography
Vmax
Maximum Volume
Vmin
Minimum Volume
Vpre
A–Pre–Atrial Contraction Volume
ρ
Spearman Correlation Coefficient

Declarations

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Ethical approval

This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Ethics Committee of Cairo University

Consent to participate

Written informed consent was obtained from all patients.

Consent to publish

The authors affirm that human research participants provided informed consent for publication of the images.

Author Contribution

M.A.M. conceived the study, collected the data, performed data analysis, and drafted the manuscript. S.R. led the cardiac magnetic resonance image acquisition and analysis, provided expert oversight in image interpretation, and contributed substantially to the imaging components of the study. M.G., K.S., A.E., A.H., and A.S. performed the balloon mitral valvuloplasty procedures and contributed to patient management and data acquisition. R.D. performed the statistical analysis and critically reviewed the manuscript. H.Y., H.K., and M.A. supervised the study, contributed to interpretation of the findings, and critically revised the manuscript. All authors reviewed and approved the final manuscript and agree to be accountable for all aspects of the work.

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Data Availability

Data supporting the findings of this study are available within the paper and its Supplementary Information.

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Figures

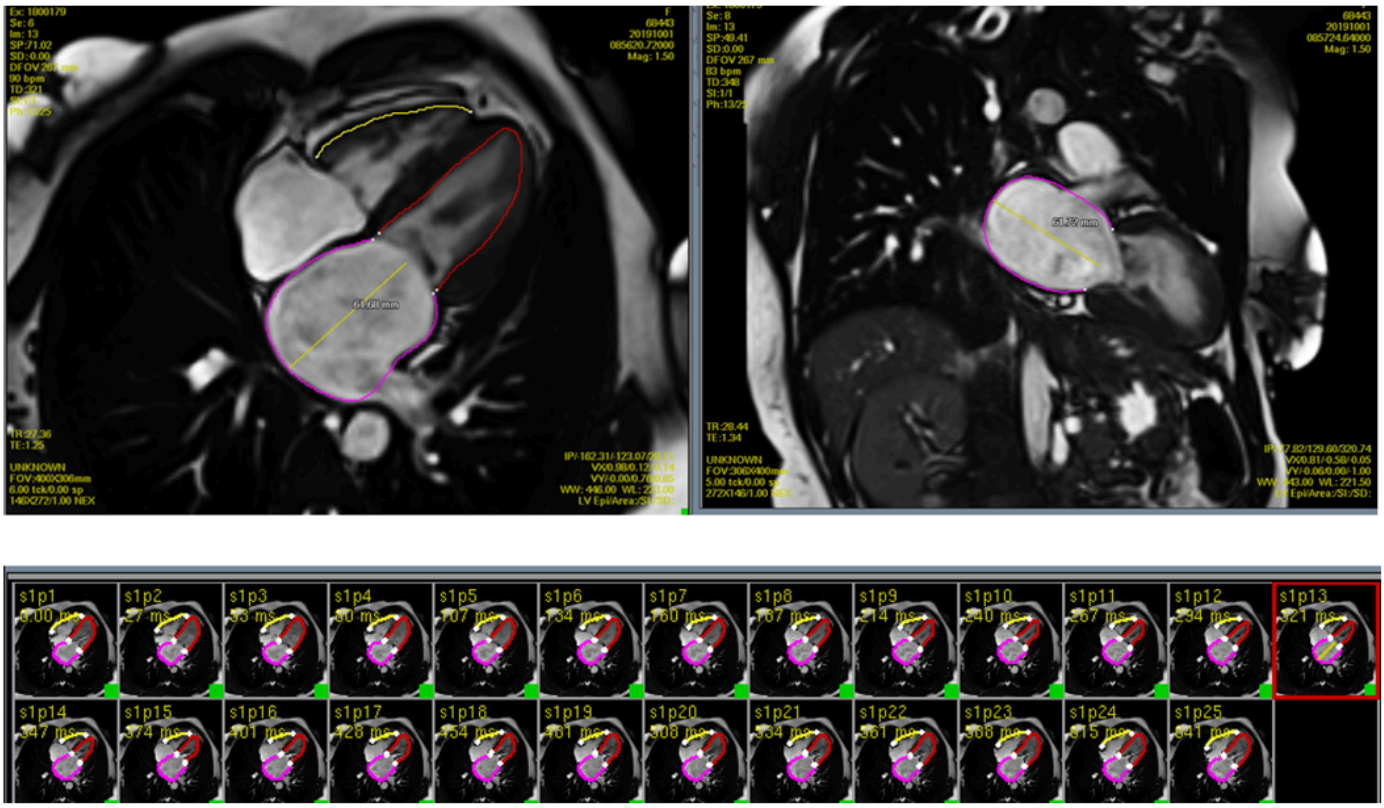


Figure 1

LA tracing in 4 and 2 chamber views. LA length is taken as the shorter long axis length (From atrial surface to midpoint of mitral annular plane). Control subject no. 4

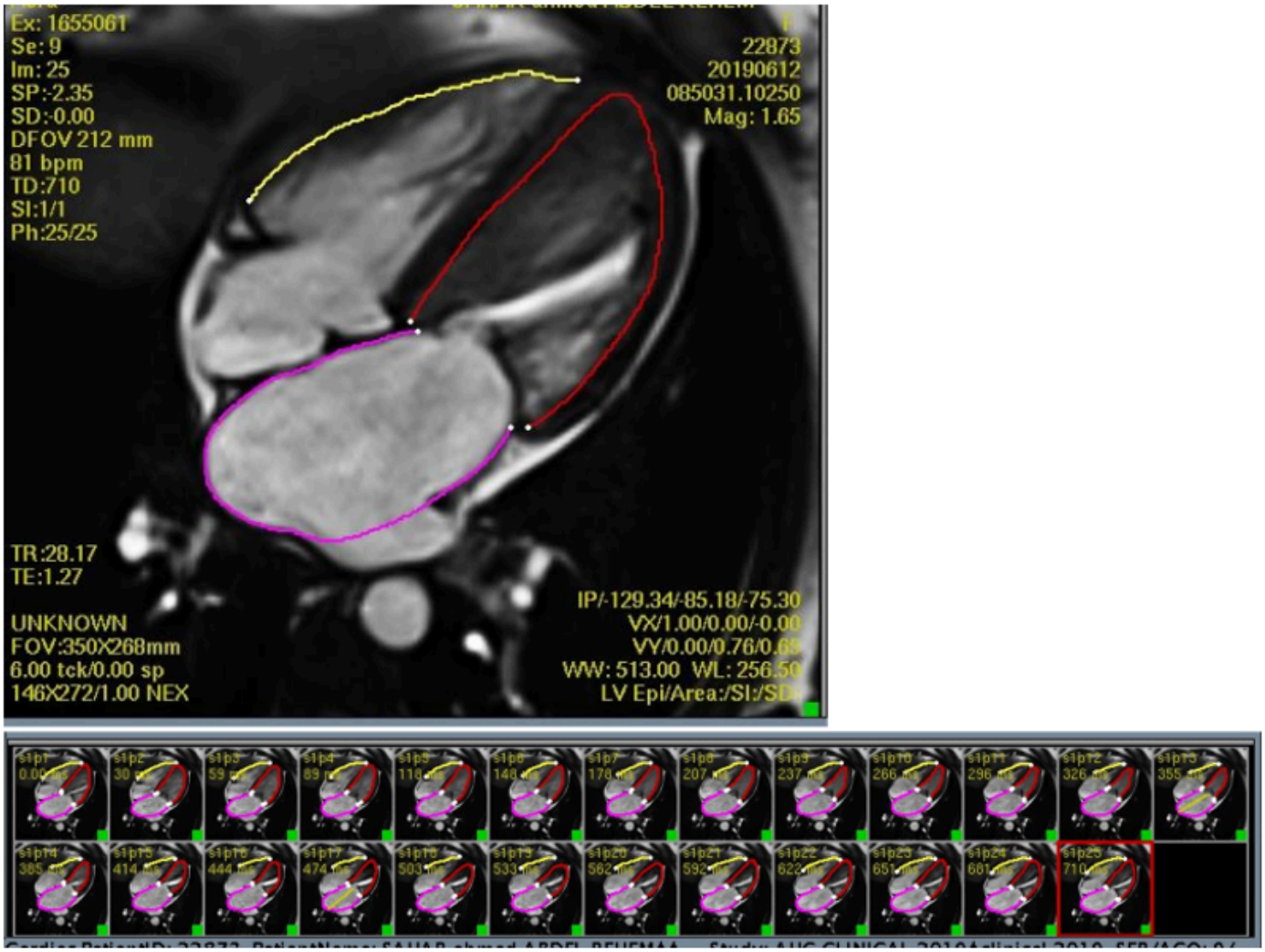


Figure 2

Left atrial tracking in the 4-chamber view in a patient with severe rheumatic mitral stenosis (Study Patient no. 22)

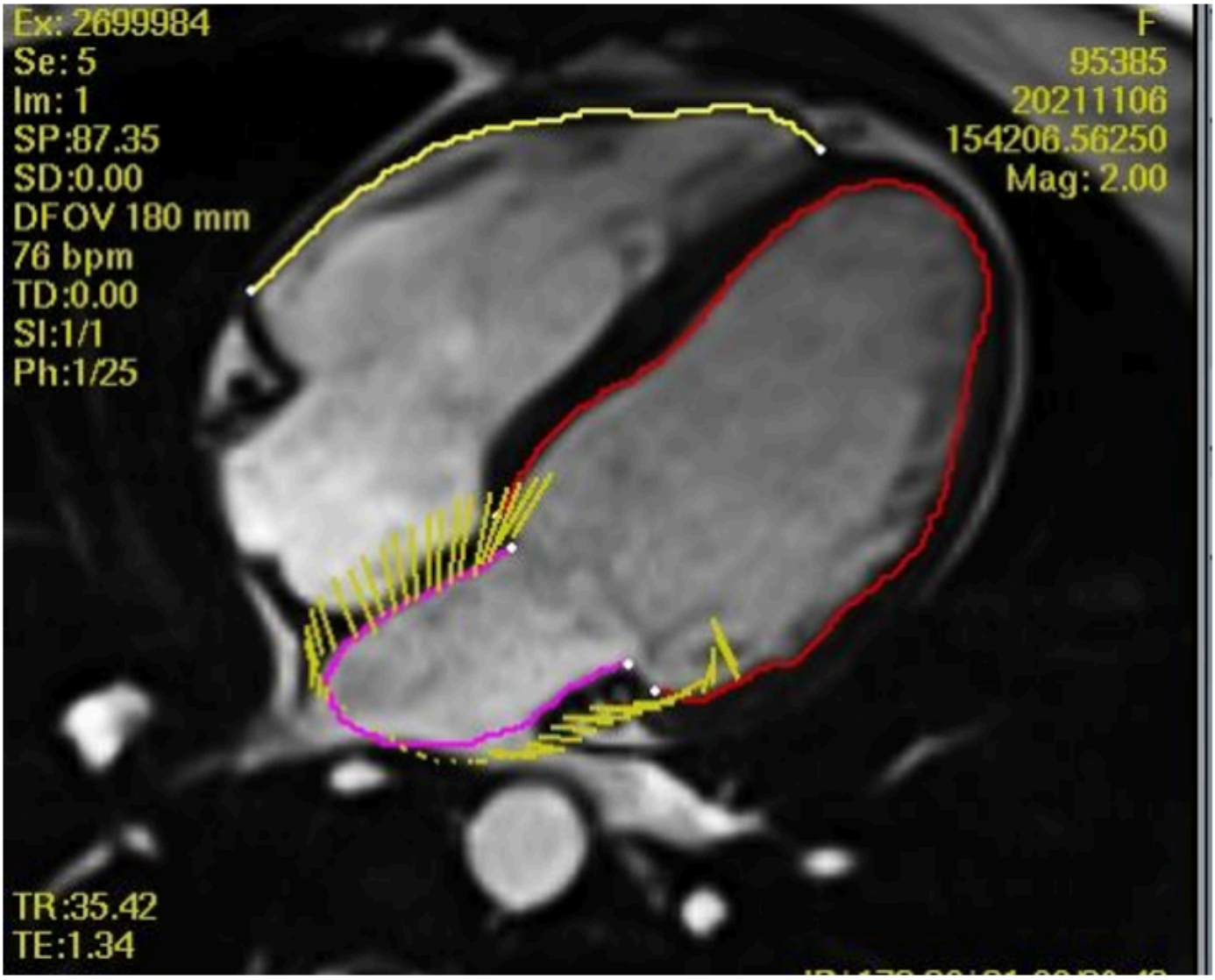


Figure 3

CMR LA Feature tracking. The figure shows a representative example of LA tracking in the 4 chamber view in control subject no. 4

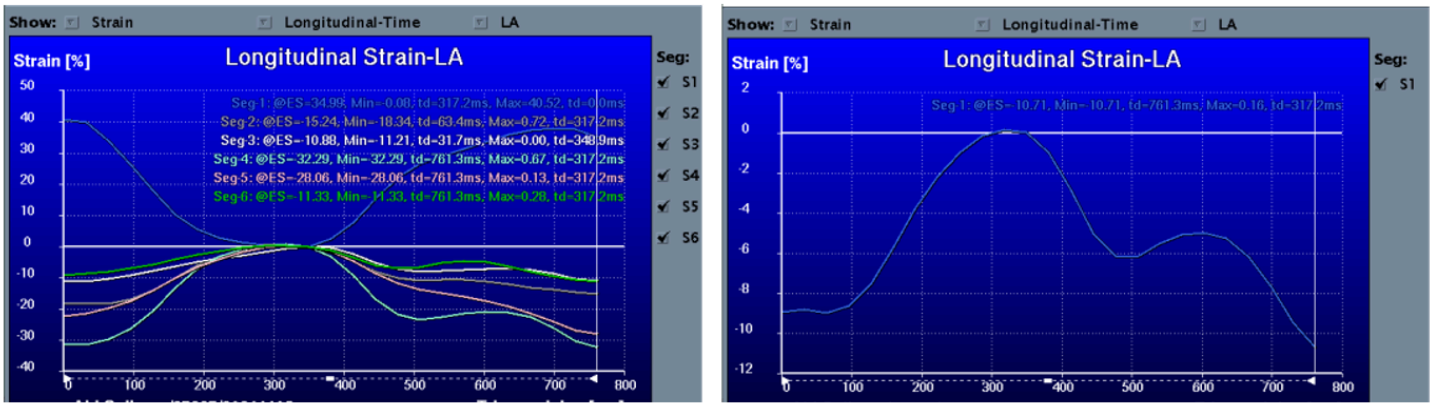


Figure 4

Strain curves for the six segments of LA (Left). Average strain curve for all segments (Right). Control subject no. 4

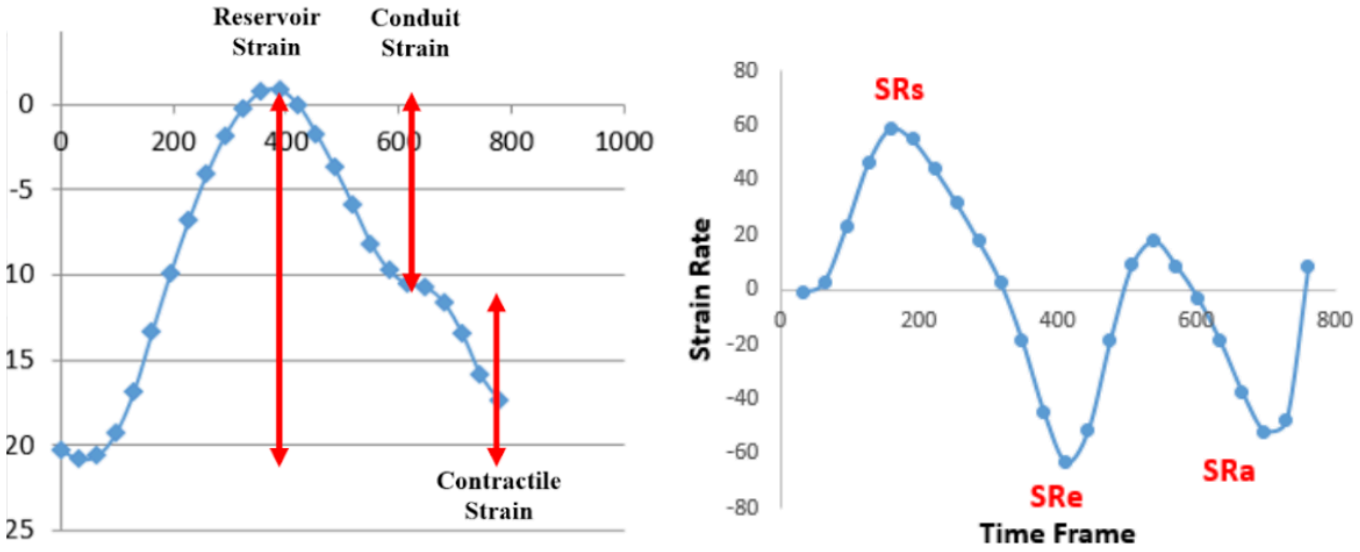


Figure 5

LA strain and strain rate profiles (Control subject no. 4)

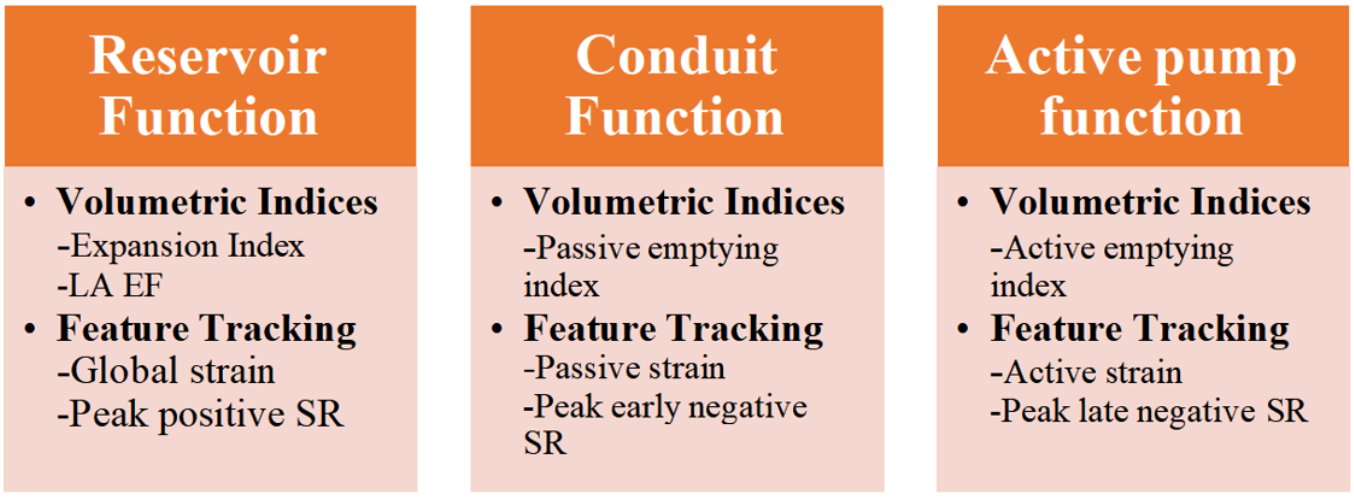


Figure 6

The 3 phasic functions of LA as assessed by volumetric and strain indices

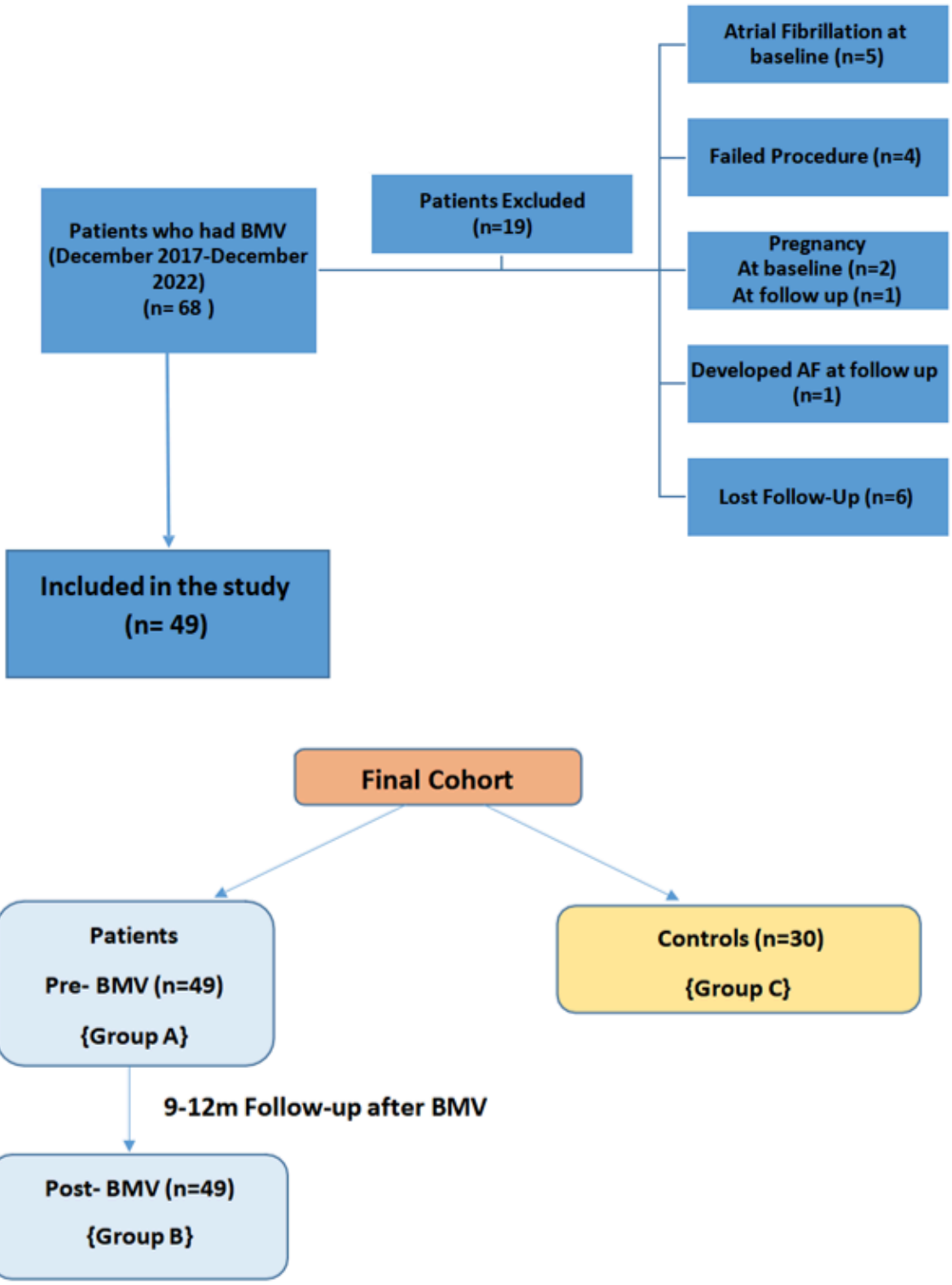


Figure 7

Flow chart for derivation of the study population cohort

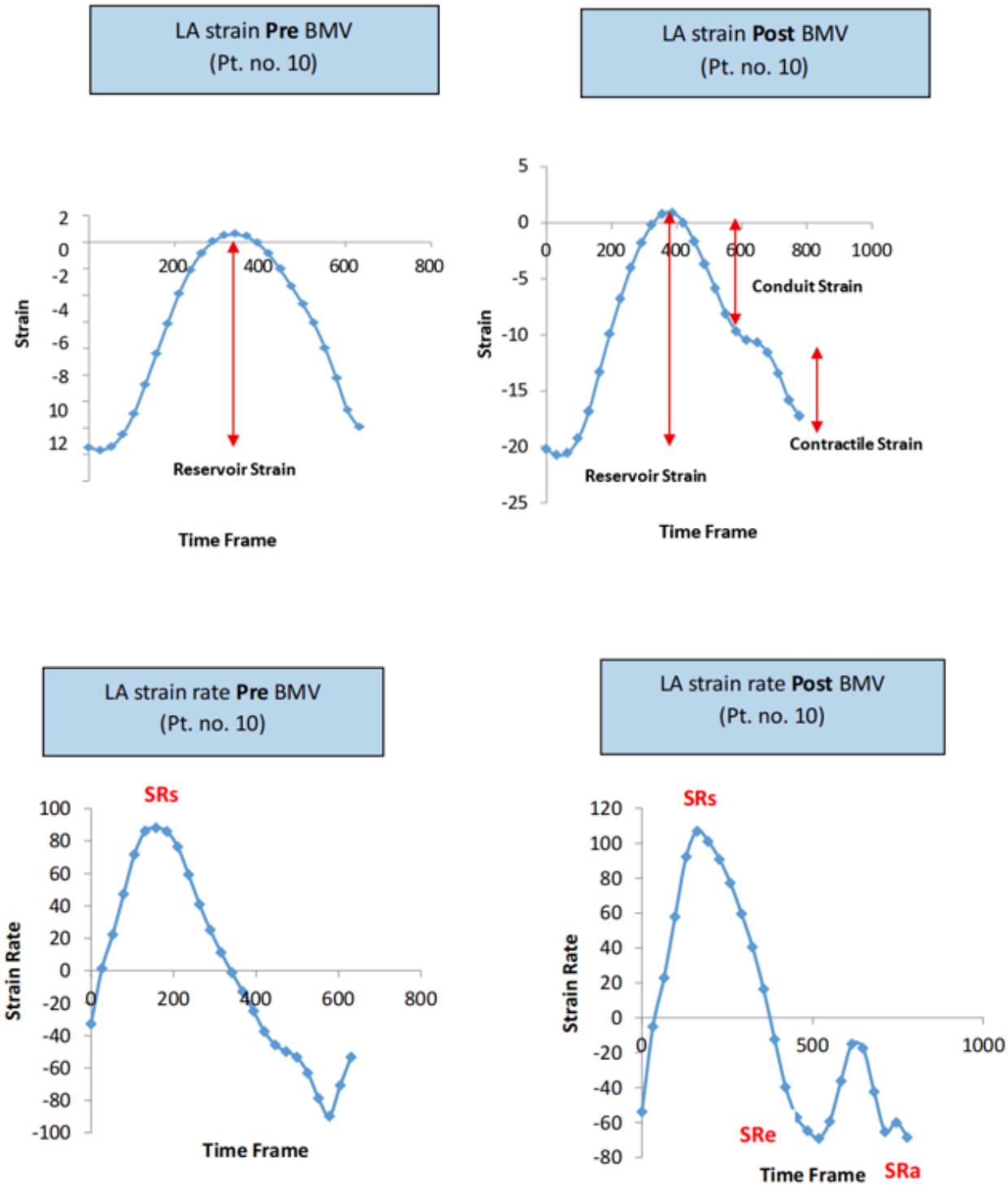


Figure 8

LA strain and SR curves before BMV (Left) and after BMV (Right) in study pt no. (10)

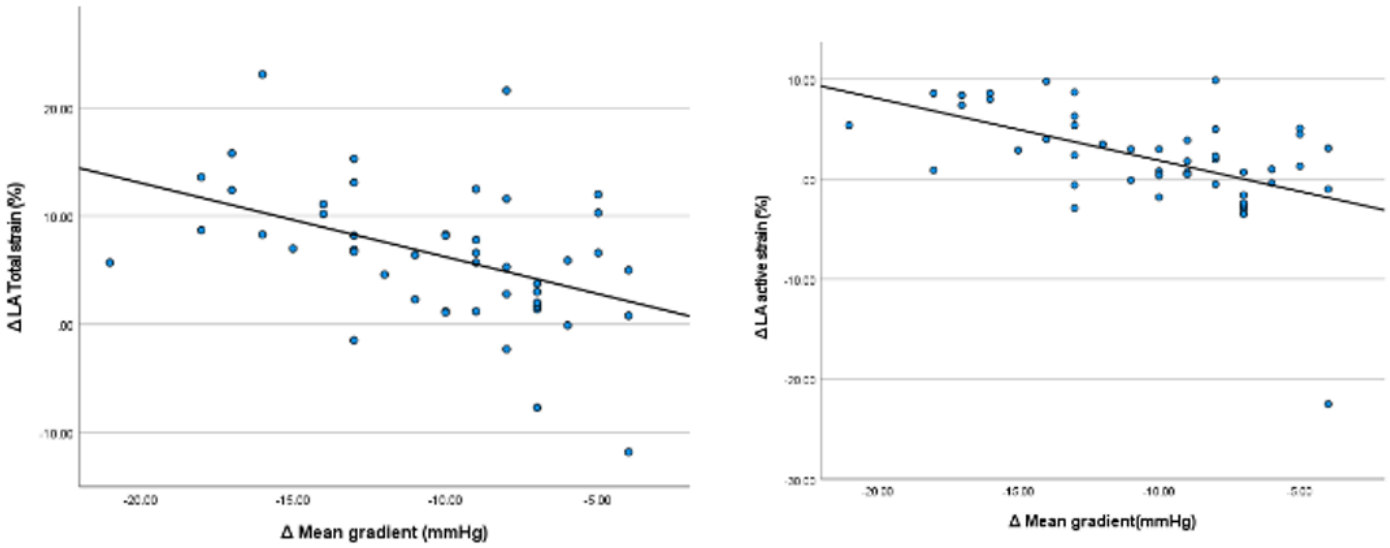


Figure 9

Correlation between delta mean gradient and delta total (reservoir) strain (Left) and active strain (right)

Supplementary Files

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- floatimage12.png