

RESEARCH

Atrial-ventricular function in rheumatic mitral regurgitation using strain imaging

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Abstract

Background: Chronic mitral regurgitation (MR) historically has been shown to primarily affect left ventricular (LV) function. The impact of increased left atrial (LA) volume in MR on morbidity and mortality has been highlighted recently, yet the LA does not feature as prominently in the current guidelines as the LV. Thus, we aimed to study LA and LV function in chronic rheumatic MR using traditional volumetric parameters and strain imaging.

Methods: Seventy-seven patients with isolated moderate or severe chronic rheumatic MR and 40 controls underwent echocardiographic examination. LV and LA function were assessed with conventional echocardiography and 2D strain imaging.

Results: LA stiffness index was greater in chronic rheumatic MR than controls (0.95 ± 1.89 vs 0.16 ± 0.13 , $P = 0.009$). LA dysfunction was noted in the reservoir, conduit, and contractile phases compared with controls ($P < 0.05$). LA peak reservoir strain (ϵ_R), LA peak contractile strain, and LV peak systolic strain were decreased in chronic rheumatic MR compared with controls ($P < 0.05$). Eighty-six percent of patients had decreased LA ϵ_R and 58% had depressed LV peak systolic strain. Decreased ϵ_R and normal LV peak systolic strain were noted in 42%. Thirteen percent had normal ϵ_R and LV peak systolic strain. One patient had normal ϵ_R with decreased LV peak systolic strain.

Conclusions: In chronic rheumatic MR, there is LA dysfunction in the reservoir, conduit, and contractile phases. In this study, LA dysfunction with or without LV dysfunction was the predominant finding, and thus, LA dysfunction may be an earlier marker of decompensation in chronic rheumatic MR.

Key Words

- ▶ left atrium
- ▶ left ventricle
- ▶ rheumatic mitral insufficiency
- ▶ strain imaging

Introduction

Chronic mitral regurgitation (MR) results in volume overload of the left ventricle (LV) and left atrium (LA) (1). The LA compensates by increasing compliance through neurohormonal modulation and undergoing structural changes such as cellular hypertrophy and interstitial fibrosis to meet the needs of the new hemodynamic load (1, 2). The LV also undergoes similar adaptation to the

increased preload (3). After a period of compensation, LA and LV dysfunction supervenes, culminating in atrial fibrillation, heart failure, and death if left untreated (4). Both the LA and LV undergo phases of compensation before reaching the lower limb of the Frank–Starling curve and irreversible remodeling (3, 5, 6, 7). In this study, we sought to simultaneously evaluate LA and

LV function in moderate or severe chronic rheumatic mitral regurgitation (CRMR) using traditional volumetric parameters and strain imaging to answer the succeeding hypothesis. We hypothesized that the temporal sequence may differ in an individual patient – in some, the LA may transition from a phase of compensation to decompensation prior to the LV, whereas in others the reverse may occur – depending on a variable combination of preload, afterload, and intrinsic characteristics of the two chambers. Therefore, the alteration in some patients' LA functional indices may serve as an early sign heralding the onset of a decompensated state. This may occur even in the presence of normal LV functional indices and absence of symptoms (2). Further, in rheumatic heart disease, we suspect that the LA hemodynamics will differ in comparison with the LA in MR due to other etiologies, secondary to involvement of the LA as part of the rheumatic pancarditis process (8, 9, 10, 11). Additionally, the impact of preoperative dual chamber dysfunction may confer greater postoperative morbidity and mortality than isolated LV or LA dysfunction. Thus, limiting surgical indications to predominantly LV parameters may result in missing the opportunity to intervene early.

Methods

This was a prospective cross-sectional study at Chris Hani Baragwanath Academic Hospital. Patients were enrolled from January 2014 through October 2014. All study patients gave written informed consent. All patients were screened, and patients deemed to have moderate or severe CRMR were referred for possible inclusion in the study. Ninety-one patients with presumed CRMR underwent clinical evaluation, resting ECG, and detailed echocardiographic assessment according to a predetermined protocol.

Inclusion criteria were age 18 years or older and echocardiographic features of moderate or severe CRMR.

Patients were excluded if any of the following comorbidities were present: significant aortic valve disease, concurrent mitral stenosis with a valve area of <2.0 cm², documented ischemic heart disease, pre-existing nonvalvular cardiomyopathy, prior cardiac surgery, congenital or pericardial disease, pregnancy, severe systemic disorders such as renal failure, uncontrolled hypertension (systolic blood pressure >140 mmHg, and diastolic blood pressure >90 mmHg) on medication, or severe anemia (hemoglobin <10 g/dL).

Fourteen patients were excluded because of the following: atrial fibrillation (*n*=2), anemia (*n*=2), renal dysfunction (*n*=3), mild MR (*n*=2), MR of non-rheumatic etiology (*n*=3), and inadequate image quality (*n*=2). The final sample included 77 patients.

Forty age- and sex-matched controls were also included. Subjects were recruited from unrelated staff at Baragwanath Hospital and volunteers who presented themselves to the echocardiography laboratory following an advertisement about this study. The inclusion criteria were absence of symptoms, normal blood pressure (≤140/90 mmHg), absence of diabetes and cardiovascular disease, absence of chronic medication, and presence of sinus rhythm (heart rate between 50–85 beats/min). The exclusion criteria were abnormal 12-lead ECGs, abnormal screening echocardiograms, and suboptimal image quality.

The study was approved by the University of the Witwatersrand Ethics Committee (M140114) and complies with the Declaration of Helsinki.

Transthoracic echocardiography was performed on all patients in the left lateral position by experienced sonographers using an S5-1 transducer on a Philips iE33 system. Images were obtained according to a standardized protocol (12). Data were transferred and analyzed offline using the Xcelera workstation (Philips).

All linear chamber measurements were performed according to the American Society of Echocardiography (ASE) chamber quantification guidelines (13). Maximum LA volume (LA_{max}) was obtained at LV end-systole from the 2D frame, just before the opening of the mitral valve (MV) (14, 15). Pre-atrial volume (V_{pre-A}) was obtained from the diastolic frame, just before the MV reopened as the result of atrial contraction (15). LA minimum volume (LA_{min}) was assessed at LV end-diastole, utilizing the smallest volume seen after LA contraction (14, 15).

LA phasic function assessment was done by using the following formulas:

- 1) *Reservoir function*: LA emptying fraction (LAEF) total = $(LA_{max} - LA_{min}) / LA_{max} \times 100\%$; expansion index = $(LA_{max} - LA_{min}) / LA_{min} \times 100\%$
- 2) *Conduit function*: passive emptying volume (PEV) = $(LA_{max} - V_{pre-A})$; passive LA emptying fraction (LAPEF) = $(LA_{max} - V_{pre-A}) / LA_{max} \times 100\%$; and conduit volume = LV stroke volume – $(LA_{max} - LA_{min})$
- 3) *Booster pump function*: LA active emptying fraction (LAAEF) = $(LA_{pre-A} - LA_{min}) / LA_{pre-A} \times 100\%$; LA active emptying volume (LA active EV) = $(V_{pre-A} - LA_{min})$ (14, 15)

All LA volumetric parameters were indexed to body surface area (BSA) (15).

LV end-diastolic volume, end-systolic volume (ESV), and ejection fraction (EF) were assessed using the Simpson's method and indexed to BSA (13). Measurements relating to LV diastolic function were performed in accordance with the ASE guidelines on diastolic function and included pulsed-wave Doppler at the mitral tips and tissue Doppler of both the medial and lateral mitral annuli (16). Measurements relating to the right ventricle (RV) were based on the ASE guidelines on the RV (17).

MR was considered rheumatic in etiology when the morphology of the valve satisfied the World Heart Federation criteria for the diagnosis of chronic rheumatic heart disease (18). MR severity was assessed using qualitative, semi-quantitative, and quantitative methods as per the ASE and European Society of Cardiology valvular regurgitation guidelines (19, 20). In equivocal cases, echocardiographic data were integrated with the clinical evaluation by an experienced cardiologist to distinguish moderate from severe MR.

Apical four- and two-chamber views were obtained using 2D greyscale echocardiography for speckle-tracking analysis (15, 21). This was performed during end-expiratory breath-hold and stable ECG recording (14, 15, 21). An adequate greyscale image that allowed separation of myocardial tissue and surrounding structures was obtained. Three consecutive cardiac cycles were recorded and averaged. The frame rate was set between 60 and 80 frames per second. Philips QLAB version 9.0 software

allowed offline semi-automated analysis of speckle-based strain. The endocardial surface of the LA was traced manually in both the four- and two-chamber views by a three-point-and-click approach. The system then automatically generated an epicardial surface tracing (15). The region of interest (ROI) was thus created and manually adjusted as needed to allow for adequate speckle tracking.

The QLAB 9 speckle-tracking software divides the ROI into seven segments in the two- and four-chamber views. It then generates the ϵ curves for each myocardial segment and subsequently an average curve of all segments (15). From these strain curves, the peak LA ϵ_R and contractile phase (ϵ_{CT}) were calculated. The peak reservoir strain of the LA was measured at LV end-systole, and the peak LA contractile strain was measured at the onset of atrial contraction (Fig. 1).

Two-dimensional echocardiographic images were obtained at end-expiration from LV apical long-axis four-, three-, and two-chamber views with frame rates between 60 and 80 frames per second (22). Three consecutive cardiac cycles were recorded and averaged (23). Peak LV longitudinal systolic strain (LVPSS) was calculated for apical long-axis views, and global LV systolic strain was calculated by averaging the three apical views as previously described (22, 24).

Four categories were created to make an assessment of simultaneous LA and LV function using peak global LA strain (LA ϵ_R) and peak global LV strain (LVPSS). These categories comprised patients with normal LA ϵ_R and LVPSS (category 1), normal LA ϵ_R with decreased

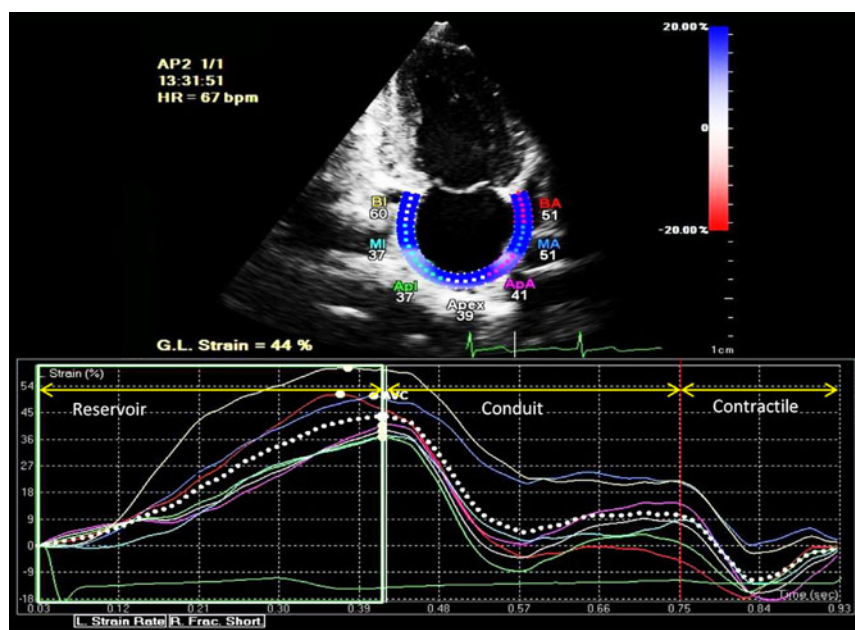


Figure 1
Apical two-chamber view of the left atrium depicting reservoir, conduit, and contractile phases.

LVPSS (category 2), decreased LA ϵ_R and LVPSS (category 3), and decreased LA ϵ_R and normal LVPSS (category 4).

The LA stiffness index was calculated noninvasively as the ratio of E/E' lateral and LA ϵ_R (25, 26).

Statistical analysis was performed with Statistica, version 12.5, series 0414 for Windows. Continuous variables are expressed as mean \pm s.d. or median (interquartile range). Student's *t*-test or Mann-Whitney *U* test were used to compare continuous variables. Categorical variables were evaluated by chi-square and Fisher's exact test when necessary.

Intraobserver and interobserver variability were assessed for peak positive LA ϵ_R , peak negative LA ϵ_{CT} , and LVPSS. Measurements were taken in 20 randomly selected subjects from the control group. To assess interobserver variability, two independent observers measured the LA volumetric and strain parameters (LA and LV), and intraobserver variability was calculated from the analysis of the same observer after 1 month of the first measurement. Interobserver and intraobserver reproducibility were assessed by calculating coefficients of variation, which were calculated as the s.d. of the differences divided by the mean. A paired *t*-test was used to compare the mean and s.d. of the values derived for strain within the control group and for LA volumes in the control group and to calculate the significance value. A *P* value of <0.05 was considered statistically significant.

Results

Clinical and echocardiographic characteristics of the study and control populations are shown in Table 1. The control arm and MR patients showed no significant difference with regard to age, sex, BMI, blood pressure, and heart rate. Moderate MR was present in 51 patients (66%) and severe MR was present in 26 (34%). LA and LV diameters and volumes were increased in the study patients compared with controls (*P*<0.05). Surrogates of LV systolic function were worse in CRMR than in controls (*S'* medial: 6.3 \pm 1.3 cm/s vs 7.1 \pm 1.6 cm/s, *P*=0.004; ESV indexed: 40.0 \pm 22.2 mL/m² vs 17.8 \pm 6.4 mL/m², *P*<0.0001). Patients with CRMR had a higher E/E' ratio than the controls (E/E' medial ratio: 20.1 \pm 10.7 vs 9.4 \pm 3.0, *P*<0.0001) as a result of higher E wave velocity (133.8 \pm 48.1 vs 77.0 \pm 17.6, *P*<0.0001). However, there was no difference in the EF between the group with MR and controls (*P*=0.07).

LA phasic volumes and functional analysis are summarized in Table 2. LA_{max}, LA_{min}, and V_{pre-a} were higher in the study patients than controls (*P*<0.0001).

However, the indices of reservoir, conduit, and contractile function were all depressed in the study patients compared with the controls (*P*<0.001). LA stiffness index was greater in the MR patients than the controls (0.95 \pm 1.89 vs 0.16 \pm 0.13, *P*=0.009).

LA and LV strain parameters are indicated in Fig. 2 and Table 2. LA ϵ_R , LA ϵ_{CT} , and LVPSS were decreased in the MR group compared with the controls (*P*=0.04) (Table 2). Eighty-six percent of MR patients had decreased LA ϵ_R (Fig. 2). Fifty-eight percent had depressed LVPSS. Thirteen percent had normal LA ϵ_R and LVPSS (category 1). One patient had normal LA ϵ_R with decreased LVPSS (category 2). Decreased LA ϵ_R and LVPSS were present in 44% of patients (category 3). Decreased LA ϵ_R and normal LVPSS were noted in 42% of patients (category 4). The aforementioned categories are depicted in Fig. 3. In patients with mitral regurgitation, there was an overall positive correlation between LA and LV peak systolic strain (*r*=0.47, *P*<0.001).

The intraobserver coefficient of variation for LA ϵ_R was 4.8% with a mean difference of 3.2 \pm 0.67 (*P*=0.3) and for LA ϵ_{CT} was 4.6% with a mean difference of 1.43 \pm 0.31 (*P*=0.3). The interobserver variability coefficient was 9% for both LA ϵ_R (*P*=0.6) and ϵ_{CT} (*P*=0.6) with mean differences of 3.2 \pm 0.35 and 1.2 \pm 0.13, respectively.

The intraobserver coefficient of variation for LVPSS was 2.4% with a mean difference of 1.1 \pm 2.7 (*P*=0.09). The interobserver variability coefficient for LVPSS was 9.8% with a mean difference of 0.25 \pm 2.4 (*P*=0.6).

Discussion

The main findings of this study are:

- 1) Absolute volumes of the LA increase compared with normal controls during the three phases, whereas the relative percentage change in volume is diminished in all phases.
- 2) Both LA ϵ_R and ϵ_{CT} were decreased in the study group compared with normal individuals.
- 3) LA ϵ_R was abnormal in the majority of patients (86%); of these, almost half (44%) had concomitant diminished LVPSS.

The LA has three main functions, namely the reservoir, conduit, and contractile functions (27). In the reservoir phase, the LA receives blood from the pulmonary veins during LV systole; in the conduit phase, there is passive emptying of blood into the LV during early diastole; and in the contractile phase, the LA actively ejects blood

Table 1 Clinical and echocardiographic characteristics of study patients.

Variable	Study patients (n = 77)	Controls (n = 40)	P value
Clinical			
Age (years)	44 ± 13.6	42 ± 13.4	0.4
Sex (male:female)	13:64	8:32	0.6
BSA (m ²)	1.7 ± 0.2	1.8 ± 0.2	0.01
BMI (kg/m ²)	27.1 ± 5.9	28.4 ± 6.2	0.3
SBP (mmHg)	124.2 ± 11.4	124 ± 12.5	0.93
DBP (mmHg)	77 ± 9.1	75.7 ± 12.6	0.52
Heart rate (beats/min)	77.1 ± 12.6	76.3 ± 14.1	0.75
NYHA (I/II/III) (%)	42/49/9	-	
Hypertension (%)	40	-	
HIV (%)	13	-	
Hypertension and HIV (%)	15	-	
Echocardiographic			
LVEDD (mm)	54.8 ± 9.4	42.5 ± 4.8	<0.0001
LVESD (mm)	41.4 ± 9.4	27.1 ± 4.2	<0.0001
IVSD (mm)	8.6 ± 2.1	9.5 ± 1.9	0.02
LVPWD (mm)	8.5 ± 1.5	9.2 ± 1.9	0.03
EDVi (mL/m ²) ^a	93.2 ± 30.1	47.9 ± 13.5	<0.0001
ESVi (mL/m ²) ^a	40.0 ± 22.2	17.8 ± 6.4	<0.0001
LAVi (mL/m ²) ^a	64.1 ± 39.9	21.9 ± 4.9	<0.0001
LVEF (%)	58.5 ± 12.9	62.8 ± 11.2	0.07
LVMi (kg/m ²) ^a	102.7 ± 36.3	65.6 ± 20.3	<0.0001
E wave (cm/s)	133.8 ± 48.1	77.0 ± 17.6	<0.0001
A wave (cm/s)	98.4 ± 33.5	59.6 ± 13.0	<0.0001
Deceleration time (ms)	214.5 ± 62.2	135.4 ± 42.3	<0.0001
E/A ratio	1.5 ± 0.6	1.3 ± 0.4	0.06
E' medial (cm/s)	7.3 ± 2.3	8.8 ± 2.8	0.002
E' lateral (cm/s)	10.1 ± 4.0	13.4 ± 3.6	<0.0001
E/E' medial (cm/s)	20.1 ± 10.7	9.4 ± 3.0	<0.0001
E/E' lateral (cm/s)	15.4 ± 8.8	5.9 ± 1.6	<0.0001
S' medial (cm/s)	6.3 ± 1.3	7.1 ± 1.6	0.004
S' lateral (cm/s)	7.3 ± 2.5	8.2 ± 2.6	0.07
PASP (mmHg)	35.1 ± 16.9	21.5 ± 6.4	<0.0001

Data presented as mean ± s.d. or %.

^aValues are indexed to BSA.

BSA, body surface area; DBP, diastolic blood pressure; EDVi, end-diastolic volume indexed; ESVi, end-systolic volume indexed; HIV, human immunodeficiency virus; IVSD, interventricular septal diameter; LAVi, left atrial volume indexed; LVEDD, left ventricular end-diastolic diameter; LVEF, left ventricular ejection fraction; LVESD, left ventricular end-systolic diameter; LVMi, left ventricular mass indexed; LVPWD, left ventricular posterior wall diameter; NYHA, New York Heart Association; PASP, pulmonary artery systolic pressure; SBP, systolic blood pressure.

into the LV in late diastole (27). MR is characterized by systolic volume overload of the LA (4, 28). In this study, volumetric measures of global LA function were increased, namely LA_{max}, LA_{min}, and V_{pre-a}. The increased LA_{max} would be expected secondary to systolic volume overload of the LA as a result of MR that occurs in addition to the normal venous return from the pulmonary veins. An increased V_{pre-A} and LA_{min} similar to that found in prior studies was noted in the present study (1, 4, 28, 29). However, there appear to be discrepancies in the literature with regard to whether the three phasic LA volumes are increased (1, 4, 28, 29). Borg *et al.*, Yurdakul *et al.*, and Ren *et al.* found an increment in the percentage change of reservoir LA volumes with preserved booster function based on volumetric indices (4, 29, 30). In contrast, both in our

study and in those of Aksakal *et al.* and Moustafa *et al.*, a relative decrement in reservoir and booster function was observed (1, 28). Of the three phases, the conduit function was preserved or increased in all the studies (1, 4, 28, 29, 30). It is possible that the similarities and differences in the phasic LA functional parameters in these studies may be attributed to a variable combination of duration and severity of MR, LV compliance, LA compliance, and the intrinsic characteristics of the LA and the LV (1, 4, 28, 29, 30, 31, 32).

It is likely that findings from the present study may relate to altered LA and LV pathophysiology in MR. In the patient exhibiting compensation with significant MR, LV diastolic function would be expected to be normal or increased to accommodate the increased blood volume

Table 2 Left atrial and ventricular peak systolic strain and left atrial volumetric and phasic functional parameters in chronic rheumatic mitral regurgitation.

Variable	CRMR (n = 77)	Control (n = 40)	P value
Volumes			
Maximum LAVi (mL/m ²) ^a	64.1 ± 39.9	21.9 ± 4.9	<0.0001
Minimum LAVi (mL/m ²) ^a	39.6 ± 35.5	8.1 ± 3.1	<0.0001
Pre-A LAVi (mL/m ²) ^a	49.4 ± 39.0	13.6 ± 4.6	<0.0001
Reservoir function			
LA total emptying volume indexed (mL/m ²) ^a	24.6 ± 13.7	15.6 ± 12	<0.001
LAEF total (%)	45.4 ± 16.5	61.2 ± 12.0	<0.0001
LA exp index (%)	98.6 ± 62.6	194.4 ± 131.8	<0.0001
Conduit function			
LAPEVi (mL/m ²) ^a	14.9 ± 13.4	8.2 ± 4.4	0.003
LAPEF (%)	26.7 ± 19.4	38.3 ± 14.9	0.001
Conduit volume (mL/m ²) ^a	28.8 ± 21.6	16.7 ± 9.8	<0.001
Booster function			
LA AEF (%)	24.1 ± 13.1	38.6 ± 13.4	<0.0001
LA AEVi (mL/m ²) ^a	9.7 ± 6.3	4.9 ± 2.8	<0.0001
Strain parameters			
ε _R (%)	20.7 ± 10.0	39.0 ± 7.3	<0.0001
ε _{CT} (%)	-0.5 ± 1.6	-2.28 ± 2.05	<0.0001
LV global peak systolic strain (%)	-16.1 ± 5.3	-17.9 ± 2.1	0.04
Left atrial stiffness index	0.95 ± 1.89	0.16 ± 0.13	0.009

Data presented as mean ± s.d.

^aValues are indexed to body surface area.

CRMR, chronic rheumatic mitral regurgitation; ε_{CT}, peak left atrial strain in the contractile phase; ε_R, peak left atrial strain in the reservoir phase; LA, left atrial; LA AEF, LA active emptying fraction; LA AEVi, left atrial active emptying volume index; LA exp index, left atrial expansion index; LAEF, left atrial emptying fraction; LAPEF, left atrial passive emptying fraction; LAPEVi, left atrial passive emptying volume index; LAVi, left atrial volume index; Pre-A LAVi, pre-atrial contraction left atrial volume index.

that is required to enter the LV. This ultimately causes an increase in LV end-diastolic volume, the essential step in the path to LV diastolic overload. Thus, atrial volumetric markers of conduit and booster function would be normal or even potentially relatively increased. Conversely, in the decompensated state, impaired LV systolic function will result in significant diastolic dysfunction and a high LV end-diastolic pressure that would then impair LV diastolic filling and result in higher LA volumes during these phases. The increased LA V_{pre-a} and LA_{min} observed in this study imply that atrial filling of the LV during diastole is impaired. This implies that pan-diastolic LV diastolic dysfunction can occur in patients with normal LVEF and in the absence of overt clinical LV failure. Thus, the atrial volumetric markers in diastole may serve as surrogates for impaired LV diastolic dysfunction in compensated MR patients. Prior studies and the recent ASE guidelines on LV diastolic dysfunction accentuate the difficulties of utilizing conventional mitral inflow Doppler and annular tissue Doppler parameters in MR (33). Identifying this pathophysiological phase may be important because it implies that the diastolic compliance of the LV may become affected, resulting in suboptimal early filling as reflected by impairment during the conduit phase. However, with an

impairment in LV diastolic early relaxation, atrial booster function would be expected to increase, resulting in a greater proportion of filling in late diastole, as is observed in patients with LV grade 1 diastolic dysfunction as a result of other causes, for example, hypertension. This expected increment in booster function does not occur, and this must imply either severe LV diastolic dysfunction with abbreviated late diastolic filling of the LV due to high LV late diastolic pressure or the coexistence of intrinsic LA contractile dysfunction. The former postulate is supported by the high E/E' noted in patients with MR in this study. The latter postulate may be the result of fibrosis of the LA, which contributes to LA dysfunction and may be attributed to three potential factors: aging, chronic volume overload, and the rheumatic pancarditis process itself (1, 8, 9, 10, 11, 28, 31, 32, 34, 35).

We noted a decrease in LA ε_R and ε_{CT} in the majority of the patients. Similarly, some studies report that strain during the reservoir phase increases with preserved booster strain in MR compared with a normal heart (4). These differences relate to all the reasons proposed for our volumetric findings. In this study, the decrease in ε_R can be explained as follows: (1) an increase in initial length may be expected in this cohort due to increased LA minimum

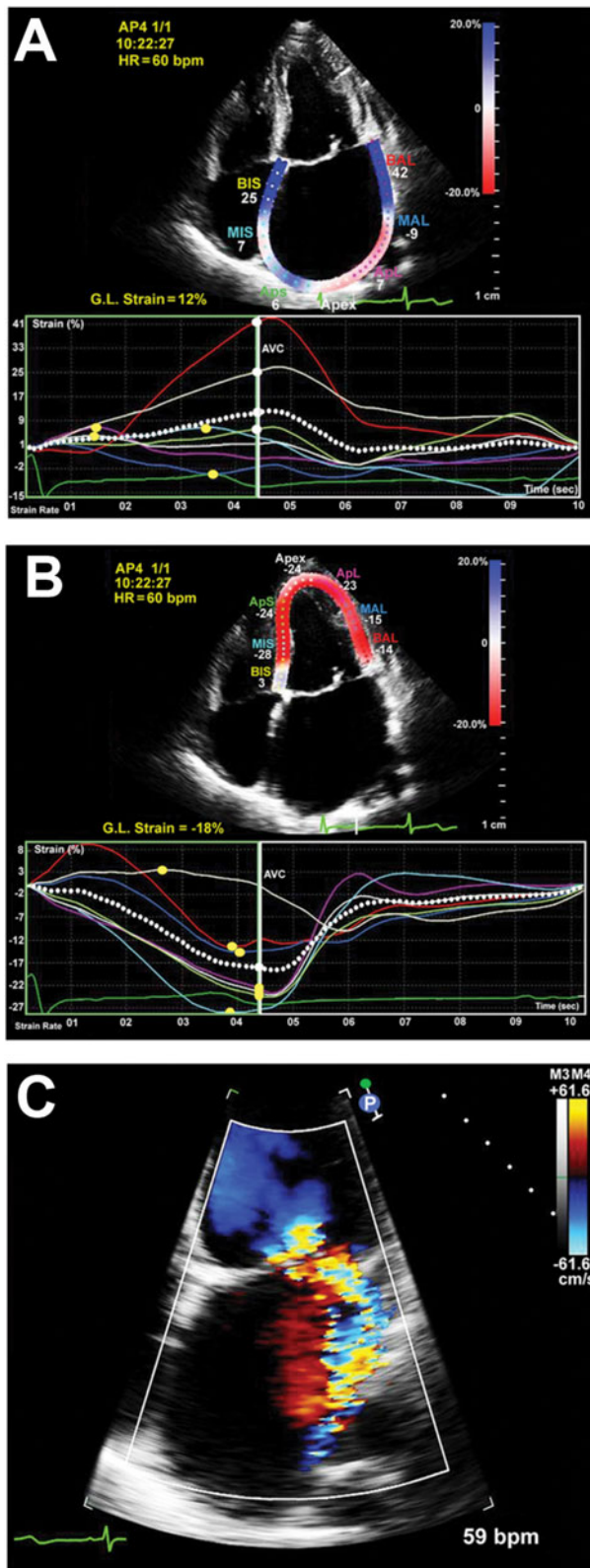


Figure 2
Decreased left atrial peak systolic strain (A) and preserved LV peak systolic strain (B) in a patient with severe rheumatic mitral regurgitation (C).

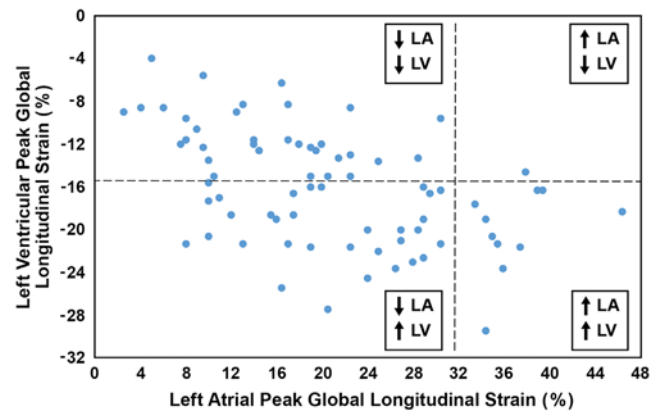


Figure 3
Four categories of left atrial (LA) and left ventricular (LV) strain were identified in patients with chronic rheumatic mitral regurgitation. Thirteen percent had normal LA ϵ_R and peak LV longitudinal systolic strain (LVPSS) (category 1). One patient had normal LA ϵ_R with decreased LVPSS (category 2). Decreased LA ϵ_R and LVPSS were present in 44% of patients (category 3). Decreased LA ϵ_R and normal LVPSS were noted in 42% of patients (category 4).

volume and (2) a decrease in the final length may be due to the decrease in mitral annular systolic descent that we observed. The latter may reflect LV longitudinal systolic impairment in MR (36, 37, 38, 39).

A second hypothesis is that intrinsic LA compliance is impaired, as evidenced by the increased LA stiffness index. Therefore, despite an increase in LA_{max} and LA_{min} , and thus the reservoir volume, the peak ϵ_R does not increase as expected owing to a limitation in the ability of the atrial wall to stretch in response to volume overload, as in the studies by Borg *et al.* and Yurdakul *et al.* (30). This, as supported by histopathology and MRI studies (31, 32), implies that the same pathophysiological process impairing relaxation of the atria (for example fibrosis) may be responsible for intrinsic abnormal atrial contractile function.

In chronic moderate or severe MR, the two main patterns noted were depressed LA reservoir strain with either normal or depressed LVPSS. This implies that LA function may decline in some patients before a decrement in LV longitudinal function occurs. This must relate to different clinical profiles among patients for the same degree of MR, for example, age-related or intrinsic abnormality of the LA compared with the LV, variable degrees of atrial fibrosis and energetics, and possible variation in neurohumoral factors. A further observation noted by Dardas *et al.* suggests that a state of decreased atrial contraction exists prior to surgery and that LA contractile performance improves after surgery even in patients with normal LVEF (40).

Thus, these four categories may serve as a guide to help in risk stratification of patients with MR according to LA and LV function prior to surgical intervention.

Our study had the following limitations: Diagnostic coronary angiogram and right and left heart catheterization were performed only on patients with an indication for surgery, MR severity was not confirmed by another modality such as cardiac MRI or 3D echocardiography, and concurrent LA and LV invasive pressures were not obtained. Finally, detailed echocardiographic assessment of LV diastolic function was not performed.

Conclusion

In CRMR, analysis of volumetric indices and strain of the LA and LV indicate that there are variable combinations of LA and LV dysfunction. The decline in LA function was related to dysfunction of the reservoir, conduit, and contractile phases and represents probable LV diastolic impairment initially. A decline in LA strain can precede a decline in LV strain and thus may suggest that LA dysfunction precedes LV systolic impairment in CRMR.

Declaration of interest

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

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References

- Aksakal E, Simsek Z, Sevimli S, Karakelleoglu S, Erol MK, Tanboga IH & Kurt M. Quantitative assessment of the left atrial myocardial deformation in patients with chronic mitral regurgitation by strain and strain rate imaging: an observational study. *Anadolu Kardiyoloji Dergisi* 2012 **12** 377–383. (<https://doi.org/10.5152/akd.2012.120>)
- Enriquez-Sarano M, Avierinos JF, Messika-Zeitoun D, Detaint D, Capps M, Nkomo V, Scott C, Schaff HV & Tajik AJ. Quantitative determinants of the outcome of asymptomatic mitral regurgitation.

- New England Journal of Medicine* 2005 **352** 875–883. (<https://doi.org/10.1056/NEJMoa041451>)
- Gaasch WH & Meyer TE. Left ventricular response to mitral regurgitation: implications for management. *Circulation* 2008 **118** 2298–2303. (<https://doi.org/10.1161/CIRCULATIONAHA.107.755942>)
- Borg AN, Pearce KA, Williams SG & Ray SG. Left atrial function and deformation in chronic primary mitral regurgitation. *European Journal of Echocardiography* 2009 **10** 833–840. (<https://doi.org/10.1093/ejehocard/jep085>)
- Nishimura RA & Tajik AJ. Evaluation of diastolic filling of left ventricle in health and disease: Doppler echocardiography is the clinician's Rosetta Stone. *Journal of the American College of Cardiology* 1997 **30** 8–18. ([https://doi.org/10.1016/s0735-1097\(97\)00144-7](https://doi.org/10.1016/s0735-1097(97)00144-7))
- Mehrzad R, Rajab M & Spodick DH. The three integrated phases of left atrial macrophysiology and their interactions. *International Journal of Molecular Sciences* 2014 **15** 15146–15160. (<https://doi.org/10.3390/ijms150915146>)
- Bonow RO, Mann DL, Zipes DP & Libby P. *Braunwald's Heart Disease: A Textbook of Cardiovascular Medicine*, 9th ed. Philadelphia, PA, USA: Saunders, 2011.
- Edwards JM & Chisholm RJ. Porcelain atrium: rheumatic heart disease. *Canadian Journal of Cardiology* 2006 **22** 267. ([https://doi.org/10.1016/s0828-282x\(06\)70909-6](https://doi.org/10.1016/s0828-282x(06)70909-6))
- Shriki J, Talkin B, Thomas IC, Farvid A & Colletti PM. Delayed gadolinium enhancement in the atrial wall: a novel finding in 3 patients with rheumatic heart disease. *Texas Heart Institute Journal* 2011 **38** 56–60.
- Roberts WC & Virmani R. Aschoff bodies at necropsy in valvular heart disease. Evidence from an analysis of 543 patients over 14 years of age that rheumatic heart disease, at least anatomically, is a disease of the mitral valve. *Circulation* 1978 **57** 803–807. (<https://doi.org/10.1161/01.cir.57.4.803>)
- Plaschkes J, Borman JB, Merin G & Milwidsky H. Giant left atrium in rheumatic heart disease: a report of 18 cases treated by mitral valve replacement. *Annals of Surgery* 1971 **174** 194–201. (<https://doi.org/10.1097/0000658-197108000-00004>)
- Otto CM. Principles of echocardiographic image acquisition and Doppler analysis. In *Textbook of Clinical Echocardiography*, 5th ed., pp. 1–30. Ed CM Otto. Philadelphia, PA, USA: Elsevier Saunders, 2013.
- Lang RM, Badano LP, Mor-Avi V, Afilalo J, Armstrong A, Ernande L, Flachskampf FA, Foster E, Goldstein SA, Kuznetsova T, *et al.* Recommendations for cardiac chamber quantification by echocardiography in adults: an update from the American Society of Echocardiography and the European Association of Cardiovascular Imaging. *Journal of the American Society of Echocardiography* 2015 **28** 1–39.e14. (<https://doi.org/10.1016/j.echo.2014.10.003>)
- Kowallick JT, Kutty S, Edelmann F, Chiribiri A, Villa A, Steinmetz M, Sohns JM, Staab W, Bettencourt N, Unterberg-Buchwald C, *et al.* Quantification of left atrial strain and strain rate using cardiovascular magnetic resonance myocardial feature tracking: a feasibility study. *Journal of Cardiovascular Magnetic Resonance* 2014 **16** 60. (<https://doi.org/10.1186/s12968-014-0060-6>)
- Vianna-Pinton R, Moreno CA, Baxter CM, Lee KS, Tsang TS & Appleton CP. Two-dimensional speckle-tracking echocardiography of the left atrium: feasibility and regional contraction and relaxation differences in normal subjects. *Journal of the American Society of Echocardiography* 2009 **22** 299–305. (<https://doi.org/10.1016/j.echo.2008.12.017>)
- Nagueh SF, Appleton CP, Gillebert TC, Marino PN, Oh JK, Smiseth OA, Waggoner AD, Flachskampf FA, Pellikka PA & Evangelista A. Recommendations for the evaluation of left ventricular diastolic function by echocardiography. *Journal of the American Society of Echocardiography* 2009 **22** 107–133. (<https://doi.org/10.1016/j.echo.2008.11.023>)

- 17 Rudski LG, Lai WW, Afilalo J, Hua L, Handschumacher MD, Chandrasekaran K, Solomon SD, Louie EK & Schiller NB. Guidelines for the echocardiographic assessment of the right heart in adults: a report from the American Society of Echocardiography endorsed by the European Association of Echocardiography, a registered branch of the European Society of Cardiology, and the Canadian Society of Echocardiography. *Journal of the American Society of Echocardiography* 2010 **23** 685–713; quiz 786–688. (<https://doi.org/10.1016/j.echo.2010.05.010>)
- 18 Remenyi B, Wilson N, Steer A, Ferreira B, Kado J, Kumar K, Lawrenson J, Maguire G, Marijon E, Mirabel M, *et al.* World Heart Federation criteria for echocardiographic diagnosis of rheumatic heart disease – an evidence-based guideline. *Nature Reviews: Cardiology* 2012 **9** 297–309. (<https://doi.org/10.1038/nrcardio.2012.7>)
- 19 Lancellotti P, Tribouilloy C, Hagendorff A, Popescu BA, Edvardsen T, Pierard LA, Badano L, Zamorano JL & Scientific Document Committee of the European Association of Cardiovascular Imaging. Recommendations for the echocardiographic assessment of native valvular regurgitation: an executive summary from the European Association of Cardiovascular Imaging. *European Heart Journal Cardiovascular Imaging* 2013 **14** 611–644. (<https://doi.org/10.1093/ehjci/jet105>)
- 20 Zoghbi WA, Enriquez-Sarano M, Foster E, Grayburn PA, Kraft CD, Levine RA, Nihoyannopoulos P, Otto CM, Quinones MA, Rakowski H, *et al.* Recommendations for evaluation of the severity of native valvular regurgitation with two-dimensional and Doppler echocardiography. *Journal of the American Society of Echocardiography* 2003 **16** 777–802. ([https://doi.org/10.1016/S0894-7317\(03\)00335-3](https://doi.org/10.1016/S0894-7317(03)00335-3))
- 21 Vieira MJ, Teixeira R, Goncalves L & Gersh BJ. Left atrial mechanics: echocardiographic assessment and clinical implications. *Journal of the American Society of Echocardiography* 2014 **27** 463–478. (<https://doi.org/10.1016/j.echo.2014.01.021>)
- 22 Younan H. Role of two dimensional strain and strain rate imaging in assessment of left ventricular systolic function in patients with rheumatic mitral stenosis and normal ejection fraction. *Egyptian Heart Journal* 2015 **67** 193–198. (<https://doi.org/10.1016/j.ehj.2014.07.003>)
- 23 Marciniak A, Claus P, Sutherland GR, Marciniak M, Karu T, Baltabaeva A, Merli E, Bijmens B & Jahangiri M. Changes in systolic left ventricular function in isolated mitral regurgitation. A strain rate imaging study. *European Heart Journal* 2007 **28** 2627–2636. (<https://doi.org/10.1093/eurheartj/ehm072>)
- 24 Kocabay G, Muraru D, Peluso D, Cucchini U, Mihaila S, Padayattil-Jose S, Gentian D, Iliceto S, Vinereanu D & Badano LP. Normal left ventricular mechanics by two-dimensional speckle-tracking echocardiography. Reference values in healthy adults. *Revista Espanola de Cardiologia* 2014 **67** 651–658. (<https://doi.org/10.1016/j.rec.2013.12.009>)
- 25 Boyd AC, Richards DA, Marwick T & Thomas L. Atrial strain rate is a sensitive measure of alterations in atrial phasic function in healthy ageing. *Heart* 2011 **97** 1513–1519. (<https://doi.org/10.1136/heartjnl-2011-300134>)
- 26 Kurt M, Wang J, Torre-Amione G & Nagueh SF. Left atrial function in diastolic heart failure. *Circulation. Cardiovascular Imaging* 2009 **2** 10–15. (<https://doi.org/10.1161/CIRCIMAGING.108.813071>)
- 27 Todaro MC, Choudhuri I, Belohlavek M, Jahangir A, Carerj S, Oreto L & Khandheria BK. New echocardiographic techniques for evaluation of left atrial mechanics. *European Heart Journal Cardiovascular Imaging* 2012 **13** 973–984. (<https://doi.org/10.1093/ehjci/jes174>)
- 28 Moustafa SE, Alharthi M, Kansal M, Deng Y, Chandrasekaran K & Mookadam F. Global left atrial dysfunction and regional heterogeneity in primary chronic mitral insufficiency. *European Journal of Echocardiography* 2011 **12** 384–393. (<https://doi.org/10.1093/ejehocard/jer033>)
- 29 Ren B, de Groot-de Laat LE & Geleijnse ML. Left atrial function in patients with mitral valve regurgitation. *American Journal of Physiology: Heart and Circulatory Physiology* 2014 **307** H1430–H1437. (<https://doi.org/10.1152/ajpheart.00389.2014>)
- 30 Yurdakul S, Yildirimturk O & Aytakin S. Left atrial mechanical functions in chronic primary mitral regurgitation patients: a velocity vector imaging-based study. *Archives of Medical Science* 2014 **10** 455–463. (<https://doi.org/10.5114/aoms.2014.43740>)
- 31 Gasparovic H, Cikes M, Kopjar T, Hlupic L, Velagic V, Milicic D, Bijmens B, Colak Z & Biocina B. Atrial apoptosis and fibrosis adversely affect atrial conduit, reservoir and contractile functions. *Interactive Cardiovascular and Thoracic Surgery* 2014 **19** 223–230; discussion 230. (<https://doi.org/10.1093/icvts/ivu095>)
- 32 Cameli M, Lisi M, Righini FM, Massoni A, Natali BM, Focardi M, Tacchini D, Geyer A, Curci V, Di Tommaso C, *et al.* Usefulness of atrial deformation analysis to predict left atrial fibrosis and endocardial thickness in patients undergoing mitral valve operations for severe mitral regurgitation secondary to mitral valve prolapse. *American Journal of Cardiology* 2013 **111** 595–601. (<https://doi.org/10.1016/j.amjcard.2012.10.049>)
- 33 Zaid RR, Barker CM, Little SH & Nagueh SF. Pre- and post-operative diastolic dysfunction in patients with valvular heart disease: diagnosis and therapeutic implications. *Journal of the American College of Cardiology* 2013 **62** 1922–1930. (<https://doi.org/10.1016/j.jacc.2013.08.1619>)
- 34 Casaclang-Verzosa G, Gersh BJ & Tsang TS. Structural and functional remodeling of the left atrium: clinical and therapeutic implications for atrial fibrillation. *Journal of the American College of Cardiology* 2008 **51** 1–11. (<https://doi.org/10.1016/j.jacc.2007.09.026>)
- 35 Thiedemann KU & Ferrans VJ. Left atrial ultrastructure in mitral valvular disease. *American Journal of Pathology* 1977 **89** 575–604.
- 36 Zaky A, Grabhorn L & Feigenbaum H. Movement of the mitral ring: a study in ultrasoundcardiography. *Cardiovascular Research* 1967 **1** 121–131. (<https://doi.org/10.1093/cvr/1.2.121>)
- 37 Simonson JS & Schiller NB. Descent of the base of the left ventricle: an echocardiographic index of left ventricular function. *Journal of the American Society of Echocardiography* 1989 **2** 25–35. ([https://doi.org/10.1016/s0894-7317\(89\)80026-4](https://doi.org/10.1016/s0894-7317(89)80026-4))
- 38 Pai RG, Bodenheimer MM, Pai SM, Koss JH & Adamick RD. Usefulness of systolic excursion of the mitral annulus as an index of left ventricular systolic function. *American Journal of Cardiology* 1991 **67** 222–224. ([https://doi.org/10.1016/0002-9149\(91\)90453-r](https://doi.org/10.1016/0002-9149(91)90453-r))
- 39 Elnoamany MF & Abdelhameed AK. Mitral annular motion as a surrogate for left ventricular function: correlation with brain natriuretic peptide levels. *European Journal of Echocardiography* 2006 **7** 187–198. (<https://doi.org/10.1016/j.euje.2005.05.005>)
- 40 Dardas PS, Pitsis AA, Tsikaderis DD, Mezilis NE, Geleris PN & Boudoulas HK. Left atrial volumes, function and work before and after mitral valve repair in chronic mitral regurgitation. *Journal of Heart Valve Disease* 2004 **13** 27–32.

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