



Contents lists available at ScienceDirect

Journal of Cardiothoracic and Vascular Anesthesia

journal homepage: [www.jcvaonline.com](http://www.jcvaonline.com)

## Original Article

# Left Atrial Strain as a Predictor of Postoperative Atrial Fibrillation After Mitral Valve Replacement for Mitral Stenosis: A Prospective Observational Study

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**Objectives:** Postoperative atrial fibrillation (POAF) is a common and serious complication following mitral valve replacement (MVR) in patients with mitral stenosis (MS). The goal of this study was to evaluate the predictive value of intraoperative left atrial (LA) strain for POAF in patients undergoing MVR for severe MS. Secondary objectives were to compare LA strain with conventional echocardiographic predictors, including LA length, LA volume, LA volume indexed (LAVi), and left atrial appendage peak flow (LAAPF) velocity, to find the optimal predictor for atrial fibrillation and LA/left atrial appendage (LAA) clot presence.

**Design:** Prospective, observational study.

**Setting:** Single tertiary care center.

**Participants:** Forty patients (38 analyzed) aged 18 to 50 years undergoing elective MVR. Patients were categorized into preoperative normal sinus rhythm (NSR) (n = 20) and preoperative atrial fibrillation (AF) groups (n = 18).

**Interventions:** LA strain, LA length, LA volume, LAVi, and LAAPF velocity were measured intraoperatively using transesophageal echocardiography, after sternotomy, prior to heparinization for cardiopulmonary bypass.

**Measurements and Main Results:** New-onset POAF occurred in 45% of patients who were in NSR preoperatively. In this group, LA reservoir strain was the only significant predictor of POAF (14.8% v 20.7%,  $p < 0.001$ ), with a strain value  $< 16.5\%$  having high predictive accuracy (area under the curve [AUC], 0.828) for new-onset POAF. In contrast, LA dimensional parameters were the best indicators of preexisting AF (AUC,  $\sim 0.71$ ), while LAAPF velocity was the superior predictor of LA/LAA clots (AUC, 0.953).

**Conclusions:** In patients with severe MS, the optimal echocardiographic predictor depends on the clinical question. LA strain is the most reliable parameter for predicting new-onset POAF in patients with sinus rhythm. In contrast, LA dimensional parameters showed the strongest correlation with preexisting AF, and LAAPF velocity is the superior predictor of LA/LAA clot. A multiparametric intraoperative assessment is therefore essential for comprehensive risk stratification.

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**Key Words:** atrial fibrillation; left atrial strain; mitral stenosis

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MITRAL STENOSIS (MS), a prevalent form of rheumatic heart disease, poses a significant clinical challenge due to the profound structural and electrical remodeling it inflicts upon the left atrium. As the disease advances and the valvular obstruction becomes hemodynamically significant, intervention becomes necessary. The therapeutic pathway typically begins with percutaneous transvenous mitral commissurotomy for suitable cases, escalating to surgical mitral valve replacement (MVR) for patients with severe or complex disease.

In MS, the left atrium (LA) is quite often affected. The gradient in the blood flow from the LA to the left ventricle (LV) results in remodeling and dilatation of the LA, which leads to mechanical, anatomic, and electrochemical changes that can be reversible or irreversible. These changes lead to dyssynchrony in the atrial muscle fibers, which manifests as atrial fibrillation (AF). The worsening LA function is thus associated with AF. The incidence of AF is 20% to 70% after mitral valve surgery.<sup>1</sup> Postoperative atrial fibrillation (POAF) is a clinical entity that deserves attention as it can lead to disastrous complications such as cardioembolic stroke, pulmonary edema, myocardial infarction, low cardiac output states, and death. Such complications will lead to a longer intensive care unit (ICU) or hospital stay. The ability to accurately predict the occurrence of AF would allow the clinician to better predict AF risk and start early antiarrhythmic prophylaxis.

Traditionally, LA size has been used as the surrogate echocardiographic marker for the prediction of AF. It is now believed that atrial function rather than atrial size could be a more direct predictor.<sup>2</sup> It has been shown that novel echocardiographic (JF) LA strain parameters are surrogate markers of the left atrial function and, therefore, of AF.<sup>3</sup> LA function has 3 distinct phases: a reservoir phase during ventricular systole, a conduit phase during early ventricular diastole, and a contractile phase during late ventricular diastole. LA reservoir strain (LASr) specifically quantifies the longitudinal stretching of the LA during ventricular systole as it fills with pulmonary venous blood. It is considered a robust marker of LA compliance and overall reservoir function.<sup>4</sup> In mitral stenosis, the chronic pressure overload leads to significant LA remodeling and a primary impairment of this reservoir function. Therefore, LASr was chosen as the primary strain parameter in this study as it most directly reflects the key pathophysiology leading to atrial dysfunction and subsequent fibrillation in this specific patient population. Furthermore, LASr has been shown to be one of the more reproducible strain measurements in clinical practice, as it corresponds to peak atrial strain, which is easier to measure.<sup>5</sup>

While numerous studies have sought to predict AF in the broad population of patients with mitral stenosis, our study deliberately focused on a more specific cohort.<sup>6–8</sup> We selected patients with isolated severe MS in normal sinus rhythm (NSR) for whom MVR was indicated. This group represents a highly specific subgroup at an exceptional risk for POAF, as they have profound, pressure overload–induced LA remodeling yet have not developed AF as part of the disease's natural history. We hypothesized that this particular cohort would be most sensitive for evaluating LA strain as a predictive parameter, allowing for a clearer understanding of its utility and the determination of potential predictive cutoff values without the confounding variables present in a more heterogeneous population.

Hence, in our study, we studied LASr using transesophageal echocardiography (TEE) in patients with severe MS as a predictor of the incidence of POAF after MVR and compared it with other known predictors such as left atrial size and left atrial appendage peak flow (LAAPF) velocity.

The primary objective of the present study was to test the hypothesis that preoperative LASr, measured by intraoperative

TEE, is a significant predictor of new-onset POAF in patients with severe MS in NSR undergoing MVR.

The secondary objectives were (1) to compare the predictive accuracy of LASr for POAF against conventional echocardiographic parameters, including LA diameter, volume, and LAAPF velocity; (2) to characterize these parameters in a parallel cohort of patients with preoperative atrial fibrillation; and (3) to identify the strongest predictor of LA/left atrial appendage (LAA) clot among the measured parameters.

## Materials and Methods

After obtaining ethical approval from the Institute Ethics Committee (IECPG-60/31.01.2023, RT-12/07.03.2023) and registering on the Clinical Trials Registry–India (CTRI/2023/07/055228), this single-center prospective, observational study was carried out between June 2023 and October 2024 in the cardiac surgery operating room (OR) of a tertiary care referral center. Forty patients with severe MS aged 18 to 50 years scheduled for elective MVR were enrolled. Patients preoperatively in normal sinus rhythm were categorized as the pre-NSR group ( $n = 20$ ), and those in atrial fibrillation were categorized as the pre-AF group ( $n = 20$ ). Patients were excluded if they had more than mild mitral regurgitation (MR), any other moderate or severe valve lesion (hemodynamically insignificant tricuspid regurgitation was permitted), congenital heart disease, significant coronary artery disease, LV dysfunction, or a history of previous cardiac surgery. Patients were also excluded from the study after recruitment if good-quality echocardiographic images could not be acquired (Fig 1). The patients were studied from preanaesthesia checkup until they were transferred out of the ICU postoperatively. The demographic and clinical preoperative parameters were noted. Echocardiography was performed using TEE for the study after sternotomy but prior to heparinization, and findings were noted. The relation of preoperative characteristics and echocardiographic findings with the postoperative occurrence of AF was studied.

## Anaesthesia Management

All patients were managed according to a standardized institutional protocol for mitral valve replacement surgery. After premedication, general anesthesia was induced with intravenous fentanyl, etomidate, and rocuronium bromide and maintained with a balanced technique using isoflurane and intermittent boluses of opioids and muscle relaxants. Standard American Society of Anesthesiologists monitoring was supplemented with invasive arterial and central venous pressure monitoring. Following induction, a TEE probe was placed for comprehensive intraoperative imaging. All surgical procedures, including the conduct of cardiopulmonary bypass (CPB) with antegrade cardioplegia, were performed using standard institutional techniques. Vasoactive and inotropic support was administered post-CPB based on clinical and echocardiographic findings to maintain hemodynamic stability. It is important to note that no patients in this study cohort underwent a concomitant MAZE procedure or any other form of surgical arrhythmia ablation.

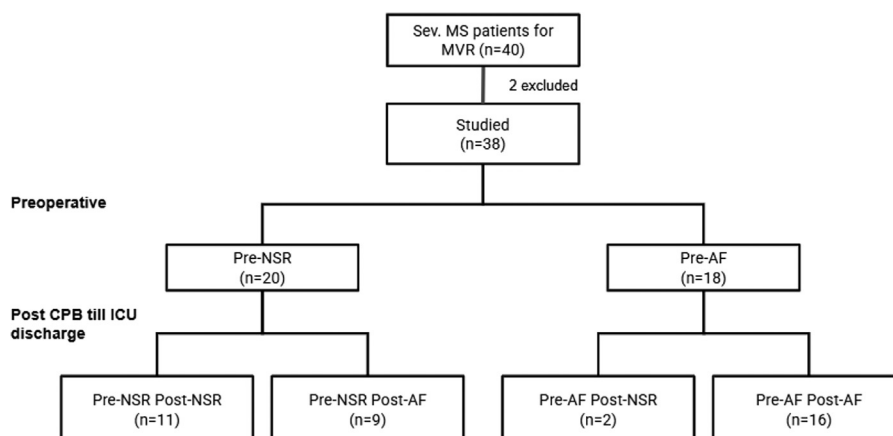


Fig 1. Patient enrollment chart. AF, atrial fibrillation; ICU, intensive care unit; MS, mitral stenosis; MVR, mitral valve replacement; NSR, normal sinus rhythm.

### Transesophageal Echocardiography

Comprehensive TEE was performed with the GE adult probe (6VT-D, 3–8 MHz) of the Vivid E95 (GE Vingmed Ultrasound AS) machine using EchoPAC 204 software. It was performed by a single expert echocardiographer with experience in performing at least 150 comprehensive TEE examinations. Specific evaluation for mitral valve disease was then performed. All study-specific echocardiographic measurements were performed after sternotomy but before pericardiotomy and heparinization.

All LA measurements were performed from the deep transgastric 4-chamber view. This view was deliberately chosen over standard mid-esophageal views to mitigate the significant LA foreshortening that can lead to underestimation of true LA length, volume, and strain. The deep transgastric view provides an imaging plane analogous to the transthoracic apical view, which is considered the gold standard, and has been validated as a reliable method for intraoperative LA quantification, showing excellent correlation with transthoracic echocardiography (TTE)–derived strain ( $r = 0.92$ ).<sup>9</sup>

LA strain analysis was done intraoperatively during image acquisition in the deep transgastric view. Region of interest (ROI) was selected by tracing the LA wall with the 3-point method, with the 3 markers (2 at both mitral annuli and 1 at the LA roof) and setting the ROI at the minimal thickness. The tracing was semiautomatic, as after automatic tracking, modifications were made manually as per the echocardiographer's perception of the LA wall outline. LA strain was automatically calculated by the Speckle Tracking Echocardiography software. The value was cross-checked by the echocardiographer by observing the shape of the graph generated. The analysis was performed intraoperatively using EchoPAC 204 on the GE Vivid E95 and postoperatively verified using the same software on the analyst's personal computer. The strain analysis feature of this software was designed for LV. We used the same for LA as it has already been proven that by optimizing ROI tracing, the same software can be reliably used for LA strain assessment. LV end-diastole was utilized as the zero-reference baseline for strain calculation, from which the peak positive longitudinal strain was measured to represent the LASr.<sup>10</sup>

LA size measurements were made in the deep transgastric view during LV end-systole. The LA length was defined as the distance from the midpoint of the line joining the mitral annuli to the roof of the LA in the 4-chamber view. LA volume was measured by focusing on the LA in a 4-chamber view and simultaneously visualizing the 2-chamber view by using the MultiD feature and performing Simpson's biplane method. The LA volume index was obtained by dividing the LA volume by the body surface area (BSA) of the patient.

LAAPF was measured by placing the cursor in the middle of the proximal one-third of the LAA, aligning with the maximum color flow signal, and acquiring a pulse-wave Doppler waveform at that point. The peak velocity at that point was considered the LAAPF velocity.

### Outcome Definition and Other Parameters Measured

The primary outcome was the development of POAF, which was defined as any episode of atrial fibrillation lasting for more than 1 hour and/or documented on continuous 5-lead electrocardiogram monitoring in the OR/ICU or captured on a standard 12-lead electrocardiogram performed for any clinical indication during the postoperative ICU stay.<sup>11</sup>

**Case duration:** The time from the start of administration of anesthesia drugs in the OR until the departure of the patient from the OR

**CPB time:** The time from the onset of CPB institution to complete weaning

**Aortic cross-clamp time:** The time duration for which the aortic cross-clamp (AXC) was applied during CPB

**Time to AF onset:** The time from weaning of CPB until the onset of AF

**Mechanical ventilation duration:** Time period from arrival of the patient in the ICU until extubation

**ICU stay duration:** Time from start of the ICU stay until transfer out of the ICU to the wards

**Vasoactive inotropic score (VIS):** A standard score depicting the amount of pharmacological hemodynamic support the patient requires, assessed by giving weightage to different vasoactive drugs based on potency and dose (Appendix)

### Sample Size Calculation

An a priori sample size estimation was performed based on previously published data on LA strain in patients undergoing mitral valve surgery. However, upon completion of the study and in light of the observed event rate, a post hoc power analysis was conducted to determine the achieved statistical power for our primary objective. The power analysis was based on the primary outcome results from the pre-NSR cohort ( $n = 20$ ), which was prospectively divided into patients who remained in NSR postoperatively (pre-NSR post-NSR group,  $n = 11$ ) and those who developed new-onset POAF (pre-NSR post-AF group,  $n = 9$ ). The calculation utilized the observed mean LASr and standard deviations for the pre-NSR post-NSR group ( $20.7\% \pm 3.2\%$ ) and the pre-NSR post-AF group ( $14.8\% \pm 5.6\%$ ). With a 2-sided significance level of 0.05, the achieved statistical power was 92%. This indicates that despite the small final group sizes, the study was sufficiently powered to detect the large observed difference in LA strain, confirming the statistical robustness of our primary finding.

### Statistical Analysis

Statistical analyses were conducted to effectively summarize and compare continuous and categorical variables. Continuous variables were described using mean  $\pm$  standard deviation (SD) when the data followed a normal distribution, while nonnormally distributed data were summarized using the median along with the interquartile range. Categorical variables were presented as frequencies and percentages to provide a clear overview of their distribution across groups. Appropriate statistical tests were employed for comparisons between groups based on the nature of the data. The independent samples *t* test was used to compare the means of continuous variables between two groups if the data were normally distributed. For nonnormally distributed continuous data or when the focus was on comparing medians, the Mann-Whitney U test, a non-parametric alternative test, was applied.

For categorical variables, statistical comparisons were made using the chi-square test when sample sizes were sufficiently large and assumptions for the test were met. In cases where these assumptions were not satisfied or the sample sizes were small, Fisher's exact test was used to ensure accuracy. When comparing proportions specifically between 2 groups, the 2-proportion *z*-test was utilized. All statistical tests were 2-sided, reflecting the potential for differences in either direction, and a *p*-value of  $\leq 0.05$  was considered to indicate statistical significance. Statistical analysis was conducted using SPSS version 28.0 (IBM Corp.).

### Results

Of the total 40 enrolled patients, 38 were analyzed. Of these, preoperatively 20 patients were in NSR, while the remaining 18 patients were in AF. Of the 20 NSR patients, 11 patients continued to remain in NSR throughout their ICU stay, while 9 patients developed POAF before being shifted out of the ICU. Of the 18 patients who were preoperatively in AF, 16 continued to be in

AF, while 2 of them reverted to NSR and continued to be in NSR until they were discharged from the ICU. Two patients were excluded from the study due to inadequate LA imaging for strain measurement. These 2 excluded patients were preoperatively in AF and continued to be in AF postoperatively (Fig 1).

### Analysis of the Studied Population

The patients were divided into several groups for multiple comparisons:

1. **Pre-NSR ( $n = 20$ ) versus pre-AF ( $n = 18$ ):** Patients who were in NSR versus those who were in AF preoperatively. Demographic parameters such as age, sex, weight, height, and BSA were comparable. The presence of coexisting mitral or tricuspid regurgitation and comorbidities was comparable between the 2 groups. With regard to treatment for AF, there was a significant difference in the use of anti-arrhythmics between the 2 groups preoperatively ( $p < 0.001$ ). The AXC time and CPB time were comparable between the 2 groups. The case duration was lower in the pre-NSR group compared to the pre-AF group ( $282.8 \pm 33.5$  v  $317.5 \pm 50.9$ ;  $p = 0.017$ ). While LA strain and LAAPF velocity were not statistically different between the 2 groups, LA size parameters were lower in the pre-NSR group compared to the pre-AF group: LA length ( $65.4 \pm 10.6$  v  $73.5 \pm 11.7$ ;  $p = 0.030$ ), LA volume ( $128.6 \pm 60.6$  v  $179.1 \pm 81.1$ ;  $p = 0.021$ ), and LA volume index ( $86.0 \pm 53.3$  v  $113.7 \pm 55.2$ ;  $p = 0.047$ ). The VIS was lower in the pre-NSR group compared to the pre-AF group on day 0 ( $6.8 \pm 2.5$  v  $8.9 \pm 3.2$ ;  $p = 0.035$ ) and day 1 ( $4.3 \pm 3.4$  v  $6.7 \pm 3.0$ ;  $p = 0.028$ ). The VIS scores on days 2, 3, and day 4 were comparable. The mechanical ventilation duration and ICU stay duration were comparable between the 2 groups (Tables 1, 2, 3, 4, and 5).
2. **Pre-NSR post-NSR ( $n = 11$ ) versus pre-NSR post-AF ( $n = 9$ ):** Among all the patients who were in NSR preoperatively, a comparison was made between those who remained in NSR and those who developed AF. Demographic parameters such as age, sex, weight, height, and BSA were comparable. The presence of coexisting mitral or tricuspid regurgitation and comorbidities was comparable between the 2 groups. The AXC time, CPB time, and case duration were comparable between the 2 groups. LA strain was higher for the pre-NSR post-NSR group compared to the pre-NSR post-AF group ( $20.7 \pm 3.2$  v  $14.8 \pm 5.6$ ;  $p = 0.008$ ). Other echocardiographic parameters, LA length, LA volume, LA volume index, and LAA peak velocity were comparable between the 2 groups. The VIS was lower in the pre-NSR post-NSR group compared to the pre-NSR post-AF group on day 1 ( $2.7 \pm 2.6$  v  $6.1 \pm 3.3$ ;  $p = 0.028$ ). The VIS on days 0, 2, 3, and 4 were comparable. The mechanical ventilation duration was shorter in the pre-NSR post-NSR group compared to the pre-NSR post-AF group ( $13.6 \pm 7.8$  v  $20.4 \pm 7.5$ ;  $p = 0.013$ ), but the ICU stay duration was comparable between the 2 groups (Tables 1, 2, 3, 4, and 5).

Table 1  
Demographic Parameters

| Characteristic        | All (N = 38)  | Group 1             |                    | Group 2                      |                            | Group 3                    |                            | Group 4              |                     | Group 5                    |                            |
|-----------------------|---------------|---------------------|--------------------|------------------------------|----------------------------|----------------------------|----------------------------|----------------------|---------------------|----------------------------|----------------------------|
|                       |               | Pre-NSR<br>(n = 20) | Pre-AF<br>(n = 18) | Pre-NSR Post-NSR<br>(n = 11) | Pre-NSR Post-AF<br>(n = 9) | Pre-AF Post-NSR<br>(n = 2) | Pre-AF Post-AF<br>(n = 16) | Post-NSR<br>(n = 13) | Post-AF<br>(n = 25) | Pre-NSR Post-AF<br>(n = 9) | Pre-AF Post-AF<br>(n = 16) |
| Age (y)               | 42.18 ± 11.76 | 38.9 ± 12.33        | 45.78 ± 10.25      | 40.82 ± 10.52                | 36.67 ± 14.56              | 40 ± 21.21                 | 46.5 ± 9.17                | 40.69 ± 11.4         | 42.96 ± 12.1        | 36.67 ± 14.56*             | 46.5 ± 9.17*               |
| Sex                   | M             | 7 (35)              | 7 (38.9)           | 5 (45.5)                     | 2 (22.2)                   | 1 (50)                     | 6 (37.5)                   | 6 (46.2)             | 8 (32)              | 2 (22.2)                   | 6 (37.5)                   |
|                       |               | 13 (65)             | 11 (61.1)          | 6 (54.5)                     | 7 (77.8)                   | 1 (50)                     | 10 (62.5)                  | 7 (53.9)             | 17 (68)             | 7 (77.8)                   | 10 (62.5)                  |
| Weight (kg)           | 56.21 ± 12.9  | 56.8 ± 14.21        | 55.56 ± 11.64      | 59.27 ± 13.45                | 53.78 ± 15.33              | 61.5 ± 24.75               | 54.81 ± 10.36              | 59.62 ± 14.23        | 54.44 ± 12.07       | 53.78 ± 15.33              | 54.81 ± 10.36              |
| Height (cm)           | 164.55 ± 5.81 | 163.8 ± 7.16        | 165.39 ± 3.82      | 163.55 ± 6.2                 | 164.11 ± 8.58              | 163 ± 7.07                 | 165.69 ± 3.52              | 163.46 ± 6.02        | 165.12 ± 5.73       | 164.11 ± 8.58              | 165.69 ± 3.52              |
| BSA (m <sup>2</sup> ) | 1.59 ± 0.2    | 1.6 ± 0.23          | 1.59 ± 0.17        | 1.63 ± 0.21                  | 1.56 ± 0.26                | 1.65 ± 0.38                | 1.58 ± 0.15                | 1.64 ± 0.22          | 1.57 ± 0.19         | 1.56 ± 0.26                | 1.58 ± 0.15                |

NOTE. Data expressed as mean ± SD or number (%).

Abbreviations: AF, atrial fibrillation; BSA, Body Surface Area; NSR, normal sinus rhythm.

\* p &lt; 0.05.

- Pre-AF post-NSR (n = 2) versus pre-AF and post-AF (n = 16):** Among the patients who were preoperatively in AF, a comparison was made between those who reverted to NSR and those who remained in AF. Demographic parameters such as age, sex, weight, height, and BSA were comparable. Although the p value was <0.05 for various parameters, because of the gross disparity between group sizes, it cannot be considered statistically significant for categorical variables. AXC time, CPB time, and case duration were comparable between the 2 groups. LA strain was higher in the pre-AF post-NSR group compared to the pre-AF post-AF group ( $20.5 \pm 0.7$  v  $15.44 \pm 2.6$ ;  $p = 0.008$ ). Other echocardiographic parameters, LA length, LA volume, LA volume index, and LAAPF velocity were comparable between the 2 groups. VIS was comparable between the 2 groups. The mechanical ventilation duration ( $10.0 \pm 2.83$  v  $17.25 \pm 5.76$ ;  $p = 0.031$ ) and ICU stay duration ( $26.0 \pm 2.8$  v  $42.7 \pm 17.2$ ;  $p = 0.024$ ) were significantly shorter for the pre-AF post-NSR group compared to the pre-AF post-AF group (Tables 1, 2, 3, 4, and 5).
- Post-NSR (n = 13) versus post-AF (n = 25):** Among all patients who were in NSR postoperatively versus all patients who were in POAF, demographic parameters such as age, sex, weight, height, and BSA were comparable. Although p value was <0.05 for various parameters, because of the gross disparity between group sizes, it cannot be considered statistically significant for categorical variables. AXC time, CPB time, and case duration were comparable between the 2 groups. LA size parameters were lower in the post-NSR group compared to the post-AF group with LA length ( $62.1 \pm 8.7$  v  $72.9 \pm 11.5$ ;  $p = 0.005$ ), LA volume ( $108.1 \pm 44.7$  v  $175.7 \pm 77.0$ ;  $p = 0.005$ ), and LA volume index ( $67.8 \pm 31.5$  v  $115.4 \pm 58.3$ ;  $p = 0.009$ ). On the other hand, LAAPF velocity ( $37.3 \pm 9.27$  v  $30.8 \pm 10.1$ ;  $p = 0.06$ ) and LA strain ( $20.7 \pm 2.95$  v  $15.2 \pm 3.8$ ;  $p < 0.001$ ) were higher in the post-NSR group compared to the post-AF group. VIS was lower in the post-NSR group compared to post-AF group on day 0 ( $6.2 \pm 2.2$  v  $8.6 \pm 3.1$ ;  $p = 0.016$ ), day 1 ( $3.1 \pm 2.5$  v  $6.6 \pm 3.1$ ;  $p = 0.002$ ), and day 2 ( $0.38 \pm 1.4$  v  $3.0 \pm 3.2$ ;  $p = 0.008$ ). The VIS score of days 3 and 4 was comparable. The mechanical ventilation duration ( $13.0 \pm 7.3$  v  $18.4 \pm 6.5$ ;  $p = 0.001$ ) and ICU stay duration ( $30.5 \pm 6.8$  v  $39.8 \pm 15.4$ ;  $p = 0.009$ ) were significantly different between the 2 groups (Tables 1, 2, 3, 4, and 5).
- Pre-NSR post-AF (n = 9) versus pre-AF post-AF (n = 16):** Among all patients who developed AF postoperatively, a comparison was made between patients who were preoperatively in NSR and those who were preoperatively in AF. The pre-NSR post-AF group had younger patients compared to the pre-AF post-AF group ( $36.7 \pm 14.6$  v  $46.5 \pm 9.2$ ;  $p = 0.049$ ), while the other demographic parameters, such as sex, weight, height, and BSA, were comparable. The presence of coexisting mitral or tricuspid regurgitation and comorbidities was comparable between the 2 groups. With regard to treatment for AF, there was a significant

Table 2  
Preoperative Parameters

| Characteristic     |   |    | All (N = 38) |  | Group 1             |                    | Group 2                      |                             | Group 3                    |                             | Group 4              |                      | Group 5                    |                            |
|--------------------|---|----|--------------|--|---------------------|--------------------|------------------------------|-----------------------------|----------------------------|-----------------------------|----------------------|----------------------|----------------------------|----------------------------|
|                    |   |    |              |  | Pre-NSR<br>(n = 20) | Pre-AF<br>(n = 18) | Pre-NSR Post-NSR<br>(n = 11) | Pre-NSR Post- AF<br>(n = 9) | Pre-AF Post-NSR<br>(n = 2) | Pre-AF Post- AF<br>(n = 16) | Post-NSR<br>(n = 13) | Post- AF<br>(n = 25) | Pre-NSR Post-AF<br>(n = 9) | Pre-AF Post-AF<br>(n = 16) |
| MR                 | N | 21 |              |  | 10 (50)             | 11 (61.11)         | 6 (54.54)                    | 4 (44.44)                   | 1 (50)                     | 10 (62.5)                   | 7 (53.84)            | 14 (56)              | 4 (44.44)                  | 10 (62.5)                  |
|                    | Y | 17 |              |  | 10 (50)             | 7 (38.88)          | 5 (45.45)                    | 5 (55.55)                   | 1 (50)                     | 6 (37.5)                    | 6 (46.15)            | 11 (44)              | 5 (55.55)                  | 6 (37.5)                   |
| TR                 | N | 12 |              |  | 7 (35)              | 5 (27.77)          | 4 (36.36)                    | 3 (33.33)                   | 1 (50)                     | 4 (25)                      | 5 (38.46)            | 7 (28)               | 3 (33.33)                  | 4 (25)                     |
|                    | Y | 26 |              |  | 13 (65)             | 13 (72.22)         | 7 (63.63)                    | 6 (66.66)                   | 1 (50)                     | 12 (75)                     | 8 (61.53)            | 18 (72)              | 6 (66.66)                  | 12 (75)                    |
| HTN                | N | 38 |              |  | 20 (100)            | 18 (100)           | 11 (100)                     | 9 (100)                     | 2 (100)                    | 16 (100)                    | 13 (100)             | 25 (100)             | 9 (100)                    | 16 (100)                   |
| DM                 | N | 37 |              |  | 20 (100)            | 17 (94.44)         | 11 (100)                     | 9 (100)                     | 2 (100)                    | 15 (93.75)                  | 13 (100)             | 24 (96)              | 9 (100)                    | 15 (93.75)                 |
|                    | Y | 1  |              |  | 0 (0)               | 1 (5.55)           | 0 (0)                        | 0 (0)                       | 0 (0)                      | 1 (6.25)                    | 0 (0)                | 1 (4)                | 0 (0)                      | 1 (6.25)                   |
| Smoking            | N | 38 |              |  | 20 (100)            | 18 (100)           | 11 (100)                     | 9 (100)                     | 2 (100)                    | 16 (100)                    | 13 (100)             | 25 (100)             | 9 (100)                    | 16 (100)                   |
| CAD                | N | 38 |              |  | 20 (100)            | 18 (100)           | 11 (100)                     | 9 (100)                     | 2 (100)                    | 16 (100)                    | 13 (100)             | 25 (100)             | 9 (100)                    | 16 (100)                   |
| TIA                | N | 36 |              |  | 20 (100)            | 16 (88.88)         | 11 (100)                     | 9 (100)                     | 2 (100)                    | 14 (87.5)                   | 13 (100)             | 23 (92)              | 9 (100)                    | 14 (87.5)                  |
|                    | Y | 2  |              |  | 0 (0)               | 2 (11.11)          | 0 (0)                        | 0 (0)                       | 0 (0)                      | 2 (12.5)                    | 0 (0)                | 2 (8)                | 0 (0)                      | 2 (12.5)                   |
| Stroke             | N | 38 |              |  | 20 (100)            | 18 (100)           | 11 (100)                     | 9 (100)                     | 2 (100)                    | 16 (100)                    | 13 (100)             | 25 (100)             | 9 (100)                    | 16 (100)                   |
| COPD               | N | 38 |              |  | 20 (100)            | 18 (100)           | 11 (100)                     | 9 (100)                     | 2 (100)                    | 16 (100)                    | 13 (100)             | 25 (100)             | 9 (100)                    | 16 (100)                   |
| Heart failure      | N | 37 |              |  | 20 (100)            | 17 (94.44)         | 11 (100)                     | 9 (100)                     | 2 (100)                    | 15 (93.75)                  | 13 (100)             | 24 (96)              | 9 (100)                    | 15 (93.75)                 |
|                    | Y | 1  |              |  | 0 (0)               | 1 (5.55)           | 0 (0)                        | 0 (0)                       | 0 (0)                      | 1 (6.25)                    | 0 (0)                | 1 (4)                | 0 (0)                      | 1 (6.25)                   |
| OSA                | N | 38 |              |  | 20 (100)            | 18 (100)           | 11 (100)                     | 9 (100)                     | 2 (100)                    | 16 (100)                    | 13 (100)             | 25 (100)             | 9 (100)                    | 16 (100)                   |
| Hypothyroid        | N | 36 |              |  | 19 (95)             | 17 (94.44)         | 10 (90.9)                    | 9 (100)                     | 2 (100)                    | 16 (100)                    | 12 (92.3)            | 24 (96)              | 9 (100)                    | 15 (93.75)                 |
|                    | Y | 2  |              |  | 1 (5)               | 1 (5.55)           | 1 (9.09)                     | 0 (0)                       | 0 (0)                      | 1 (6.25)                    | 1 (7.69)             | 1 (4)                | 0 (0)                      | 1 (6.25)                   |
| H/o cardioversion  | N | 38 |              |  | 20 (100)            | 18 (100)           | 11 (100)                     | 9 (100)                     | 2 (100)                    | 16 (100)                    | 13 (100)             | 25 (100)             | 9 (100)                    | 16 (100)                   |
| H/o ablation       | N | 38 |              |  | 20 (100)            | 18 (100)           | 11 (100)                     | 9 (100)                     | 2 (100)                    | 16 (100)                    | 13 (100)             | 25 (100)             | 9 (100)                    | 16 (100)                   |
| H/o PTMC           | N | 31 |              |  | 18 (90)             | 13 (72.22)         | 10 (90.9)                    | 8 (88.88)                   | 2 (100)                    | 11 (68.75)                  | 12 (92.3)            | 19 (76)              | 8 (88.88)                  | 11 (68.75)                 |
|                    | Y | 7  |              |  | 2 (10)              | 5 (27.77)          | 1 (9.09)                     | 1 (11.11)                   | 0 (0)                      | 5 (31.25)                   | 1 (7.69)             | 6 (24)               | 1 (11.11)                  | 5 (31.25)                  |
| H/o CMV            | N | 37 |              |  | 20 (100)            | 17 (94.44)         | 11 (100)                     | 9 (100)                     | 2 (100)                    | 15 (93.75)                  | 13 (100)             | 24 (96)              | 9 (100)                    | 15 (93.75)                 |
|                    | Y | 1  |              |  | 0 (0)               | 1 (5.55)           | 0 (0)                        | 0 (0)                       | 0 (0)                      | 1 (6.25)                    | 0 (0)                | 1 (4)                | 0 (0)                      | 1 (6.25)                   |
| On antiarrhythmics | N | 27 |              |  | 20 (100)***         | 7 (38.88)***       | 11 (100)                     | 9 (100)                     | 1 (50)                     | 6 (37.5)                    | 12 (92.3)            | 15 (60)              | 9 (100)                    | 6 (37.5)                   |
|                    | Y | 11 |              |  | 0 (0)***            | 11 (61.11)***      | 0 (0)                        | 0 (0)                       | 1 (50)                     | 10 (62.5)                   | 1 (7.69)             | 10 (40)              | 0 (0)                      | 10 (62.5)                  |

NOTE. Data expressed as number (%).

Abbreviations: AF, atrial fibrillation; CAD, coronary artery disease; CMV, closed mitral valvotomy; COPD, chronic obstructive pulmonary disease; DM, diabetes mellitus; HTN, hypertension; H/o, History of; MR, mitral regurgitation; N, no; NSR, normal sinus rhythm; OSA, obstructive sleep apnea; PTMC, percutaneous transvenous mitral commissurotomy; TIA, transient ischemic attack; TR, tricuspid regurgitation; Y, yes.

\*\*\* p < 0.001.

Table 3  
Intraoperative Parameters

| Characteristic | All (N = 38)   | Group 1              |                     | Group 2                      |                             | Group 3                    |                             | Group 4              |                      | Group 5                    |                            |
|----------------|----------------|----------------------|---------------------|------------------------------|-----------------------------|----------------------------|-----------------------------|----------------------|----------------------|----------------------------|----------------------------|
|                |                | Pre- NSR<br>(n = 20) | Pre- AF<br>(n = 18) | Pre-NSR Post-NSR<br>(n = 11) | Pre-NSR Post- AF<br>(n = 9) | Pre-AF Post-NSR<br>(n = 2) | Pre-AF Post- AF<br>(n = 16) | Post-NSR<br>(n = 13) | Post- AF<br>(n = 25) | Pre-NSR Post-AF<br>(n = 9) | Pre-AF Post-AF<br>(n = 16) |
| Case duration  | 299.21 ± 45.57 | 282.75 ± 33.54*      | 317.5 ± 50.88*      | 285.9 ± 33.22                | 278.89 ± 35.51              | 262.5 ± 31.81              | 324.37 ± 49.12              | 282.3 ± 32.88        | 308 ± 49.24          | 278.88 ± 35.51*            | 324.37 ± 49.12*            |
| AXC time       | 77.71 ± 11.74  | 77 ± 11.16           | 78.5 ± 12.61        | 74.54 ± 12.13                | 80 ± 9.68                   | 70 ± 11.31                 | 79.56 ± 12.68               | 73.84 ± 11.67        | 79.72 ± 11.48        | 80 ± 9.68                  | 79.56 ± 12.68              |
| CPB time       | 119.97 ± 19.05 | 118 ± 17.75          | 122.17 ± 20.7       | 118.63 ± 16.44               | 117.22 ± 20.17              | 107.5 ± 17.67              | 124 ± 20.8                  | 116.92 ± 16.39       | 121.56 ± 20.42       | 117.22 ± 20.17             | 124 ± 20.8                 |

NOTE. Data expressed as mean ± SD.

Abbreviations: AF, atrial fibrillation; AXC, aortic cross-clamp; CPB, cardiopulmonary bypass; NSR, normal sinus rhythm.

\*p < 0.05.

Table 4  
Echocardiographic Parameters

| Characteristic               | All (N = 38)   | Group 1             |                    | Group 2                      |                             | Group 3                    |                             | Group 4              |                      | Group 5                    |                            |
|------------------------------|----------------|---------------------|--------------------|------------------------------|-----------------------------|----------------------------|-----------------------------|----------------------|----------------------|----------------------------|----------------------------|
|                              |                | Pre-NSR<br>(n = 20) | Pre-AF<br>(n = 18) | Pre-NSR Post-NSR<br>(n = 11) | Pre-NSR Post- AF<br>(n = 9) | Pre-AF Post-NSR<br>(n = 2) | Pre-AF Post- AF<br>(n = 16) | Post-NSR<br>(n = 13) | Post- AF<br>(n = 25) | Pre-NSR Post-AF<br>(n = 9) | Pre-AF Post-AF<br>(n = 16) |
| LA length (mm)               | 69.21 ± 11.71  | 65.35 ± 10.6*       | 73.5 ± 11.65*      | 61.54 ± 8.26                 | 70 ± 11.72                  | 65 ± 14.14                 | 74.56 ± 11.38               | 62.07 ± 8.67**       | 72.92 ± 11.48**      | 70 ± 11.72                 | 74.56 ± 11.38              |
| LA volume (mm <sup>3</sup> ) | 152.55 ± 74.54 | 128.63 ± 60.55*     | 179.12 ± 81.07*    | 104.94 ± 41.98               | 157.59 ± 69.22              | 125.33 ± 75.43             | 185.84 ± 81.45              | 108.08 ± 44.73**     | 175.67 ± 77.04**     | 157.59 ± 69.22             | 185.84 ± 81.45             |
| LAVi                         | 99.12 ± 55.27  | 86.03 ± 53.28*      | 113.65 ± 55.23*    | 66.91 ± 33.17                | 109.4 ± 65.2                | 72.43 ± 29.16              | 118.8 ± 56.08               | 67.76 ± 31.49**      | 115.42 ± 58.34**     | 109.4 ± 65.2               | 118.8 ± 56.08              |
| LAAPF velocity               | 33.03 ± 10.17  | 35.75 ± 8.77        | 30 ± 10.98         | 38.63 ± 8.39                 | 32.22 ± 8.33                | 30 ± 14.14                 | 30 ± 11.1                   | 37.3 ± 9.26          | 30.8 ± 10.07         | 32.22 ± 8.33               | 30 ± 11.1                  |
| LA strain                    | 17.08 ± 4.4    | 18.05 ± 5.28        | 16 ± 2.91          | 20.72 ± 3.22***              | 14.77 ± 5.6***              | 20.5 ± 0.7**               | 15.43 ± 2.55**              | 20.69 ± 2.95***      | 15.2 ± 3.82***       | 14.77 ± 5.6                | 15.43 ± 2.55               |

Data expressed as mean ± SD.

Abbreviations: AF, atrial fibrillation; LA, left atrium; LAAPF, left atrial appendage peak flow; LAVi, LA volume indexed; NSR, normal sinus rhythm.

\*p < 0.05.

\*\*p < 0.01.

\*\*\*p < 0.001.

Table 5  
Postoperative Parameters

| Characteristic                  | Group 1             |                    | Group 2                      |                            | Group 3                    |                            | Group 4              |                     | Group 5                    |                            |
|---------------------------------|---------------------|--------------------|------------------------------|----------------------------|----------------------------|----------------------------|----------------------|---------------------|----------------------------|----------------------------|
|                                 | Pre-NSR<br>(n = 20) | Pre-AF<br>(n = 18) | Pre-NSR Post-NSR<br>(n = 11) | Pre-NSR Post-AF<br>(n = 9) | Pre-AF Post-NSR<br>(n = 2) | Pre-AF Post-AF<br>(n = 16) | Post-NSR<br>(n = 13) | Post-AF<br>(n = 25) | Pre-NSR Post-AF<br>(n = 9) | Pre-AF Post-AF<br>(n = 16) |
| VIS D0                          | 7.76 ± 3.01         | 8.88 ± 3.23*       | 5.9 ± 2.02                   | 7.77 ± 2.63                | 7.5 ± 3.53                 | 9.06 ± 3.27                | 6.15 ± 2.19*         | 8.6 ± 3.06*         | 7.77 ± 2.63                | 9.06 ± 3.27                |
| VIS D1                          | 5.39 ± 3.37         | 6.66 ± 2.97*       | 2.72 ± 2.61*                 | 6.11 ± 3.33*               | 5 ± 0                      | 6.87 ± 3.09                | 3.07 ± 2.53**        | 6.6 ± 3.13**        | 6.11 ± 3.33                | 6.87 ± 3.09                |
| VIS D2                          | 2.11 ± 2.99         | 3.05 ± 3.48        | 0.45 ± 1.5                   | 2.22 ± 2.63                | 0 ± 0                      | 3.43 ± 3.52                | 0.38 ± 1.38**        | 3.0 ± 3.22**        | 2.22 ± 2.63                | 3.43 ± 3.52                |
| VIS D3                          | 0.53 ± 1.56         | 0.83 ± 1.91        | 0 ± 0                        | 0.55 ± 1.66                | 0 ± 0                      | 0.93 ± 2.01                | 0 ± 0                | 0.8 ± 1.87          | 0.55 ± 1.66                | 0.93 ± 2.01                |
| VIS D4                          | 0.26 ± 1.13         | 0.55 ± 1.61        | 0 ± 0                        | 0 ± 0                      | 0 ± 0                      | 0.62 ± 1.7                 | 0 ± 0                | 0.4 ± 1.38          | 0 ± 0                      | 0.62 ± 1.7                 |
| Mechanical ventilation duration | 16.55 ± 7.15        | 16.44 ± 5.93       | 13.54 ± 7.81*                | 20.44 ± 7.46*              | 10 ± 2.82*                 | 17.25 ± 5.75*              | 13 ± 7.3***          | 18.4 ± 6.46***      | 20.44 ± 7.46               | 17.25 ± 5.75               |
| ICU stay duration               | 36.66 ± 13.73       | 32.9 ± 8.74        | 31.36 ± 7                    | 34.77 ± 10.62              | 26 ± 2.82*                 | 42.68 ± 17.16*             | 30.53 ± 6.75**       | 39.84 ± 15.39**     | 34.77 ± 10.62              | 42.68 ± 17.16              |

Data expressed as mean ± SD.

Abbreviations: AF, atrial fibrillation; D, day; ICU, intensive care unit; NSR, normal sinus rhythm; VIS, vasoactive inotropic score.

\*  $p < 0.05$ .\*\*  $p < 0.01$ .

difference in the use of antiarrhythmics between the 2 groups ( $p < 0.001$ ). AXC time and CPB time were comparable between the 2 groups, while case duration was significantly different ( $278.9 \pm 35.5$  v  $324.4 \pm 49.1$ ;  $p = 0.023$ ). All echocardiographic parameters were comparable between the 2 groups. The VIS throughout the ICU stay, mechanical ventilation duration, and ICU stay duration were comparable between the 2 groups (Tables 1, 2, 3, 4, and 5).

**Correlation of LA strain with other echocardiographic parameters:** A statistically significant correlation was found between LA strain and the other echocardiographic parameters. A negative correlation was observed between LA length and LA strain ( $r = -0.347$ ,  $p = 0.033$ ), LA volume and LA strain ( $r = -0.370$ ,  $p = 0.022$ ), and LA volume index and LA strain ( $r = -0.359$ ,  $p = 0.027$ ). Conversely, a positive correlation was demonstrated between LAAPF velocity and LA strain ( $r = 0.527$ ,  $p = 0.001$ ) (Table 6).

**Echocardiographic correlates of preexisting AF:** Receiver operating characteristic (ROC) curve analysis of the echocardiographic parameters in comparison 1 (pre-NSR v pre-AF) was performed (Fig 2). LA length and LA volume show statistically significant area under the curve (AUC) values ( $p < 0.05$ ), with AUCs around 0.71 indicating good discriminatory power for preexisting AF. LA volume indexed also shows significance ( $p = 0.047$ ) for preexisting AF. LAAPF velocity and LA strain have AUCs below 0.4, suggesting poor discriminatory power, and are not statistically

Table 6  
Correlation of LA Strain With Other Echocardiographic Parameters

| Characteristic | r      | p value |
|----------------|--------|---------|
| LA length      | -0.347 | 0.033   |
| LA volume      | -0.370 | 0.022   |
| LAVi           | -0.359 | 0.027   |
| LAAPF velocity | 0.527  | 0.001   |

Abbreviations: LA, left atrium; LAAPF, left atrial appendage peak flow; LAVi, left atrium volume indexed.

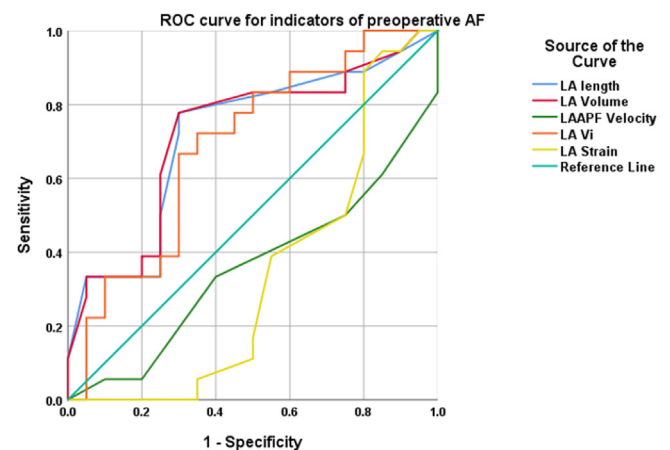


Fig 2. Echocardiographic indicators of preexisting atrial fibrillation.

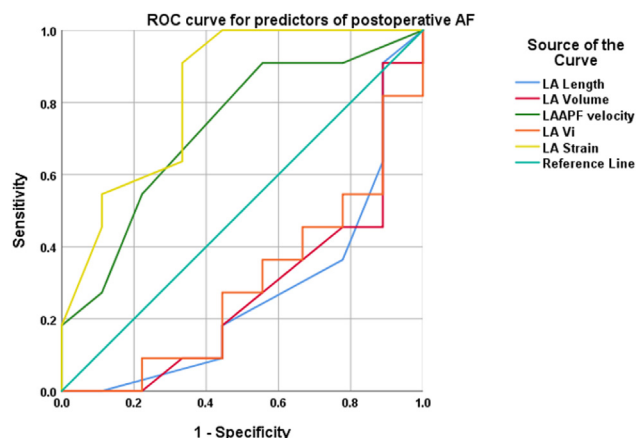


Fig 3. Echocardiographic predictors of postoperative atrial fibrillation.

significant ( $p > 0.05$ ) for preexisting AF. Among the parameters studied, LA volume was most strongly correlated with the presence of preexisting AF.

**Echocardiographic predictors of POAF:** ROC curve analysis of the echocardiographic parameters in comparison 2 (pre-NSR post-NSR *v* pre-NSR post-AF) demonstrated LA strain exhibits the highest AUC of 0.828, signifying its enhanced predictive capacity among the analyzed variables, followed by LAAPF velocity, with an AUC of 0.727 (Fig 3). Conversely, LA length, LA volume, and LA volume indexed demonstrated lower AUC values (0.268, 0.273, and 0.293, respectively). LA strain cutoff of 16.50 or less was identified as the optimal threshold for predicting a high risk of POAF, based on the highest Youden index of 0.576.

**Predictors of the presence of an LA clot:** Logistic regression analysis identified LAAPF velocity as a statistically significant predictor of LA clot presence ( $p = 0.001$ ; odds ratio, 0.739; 95% CI, 0.618–0.882). This suggests a protective effect, where higher LAAPF velocity was associated with lower odds of LA clot. In contrast, LA strain was not a significant predictor ( $p = 0.153$ ; odds ratio, 0.883; 95% CI, 0.744–1.048) of LA clot. ROC curve analysis further supported these findings, with lower LAAPF velocity demonstrating a superior ability to predict LA clot (AUC, 0.953) compared to LA strain (AUC, 0.657). While LAAPF velocity showed a high discriminatory power for LA clot, it is noteworthy that novel parameters such as LA strain did not demonstrate superiority or additional predictive value over this established hemodynamic marker.

## Discussion

Our study's findings champion a nuanced, multiparametric approach to the perioperative assessment of the left atrium in patients with severe mitral stenosis. We demonstrate that the utility of a given echocardiographic parameter is highly dependent on the specific clinical question being addressed—whether it is the risk of new-onset arrhythmia, the presence of chronic remodeling, or the potential for thrombosis. Our data suggest that relying on a single measurement is insufficient for comprehensive risk stratification.

The incidence of new-onset POAF in our pre-NSR cohort (45%) was comparable to that reported in previous studies of mitral valve surgery.<sup>1</sup> This finding, along with the observation that patients who developed AF had worse postoperative outcomes (higher inotropic requirements, longer ventilation and ICU stay), reinforces the clinical importance of identifying reliable preoperative predictors.<sup>12</sup>

Among the patients in NSR preoperatively, LA dimensions were comparable whether the patient developed POAF or remained in NSR postoperatively. However, LA strain was decreased in patients who developed POAF (14.78% *v* 20.73%). It is important to note that lower strain values are pathological, indicating a stiffer, more fibrotic, and less compliant atrium, which provides the substrate for AF. Conversely, higher strain values reflect a healthier, more elastic atrium. Thus, LA strain was determined to be a reliable predictor of POAF in such patients. Our analysis suggests that LA strain values below 16.5% indicate a significant risk for the development of POAF.

In stark contrast, our study also demonstrates that for patients with established, preexisting AF, traditional LA dimensional parameters were the best indicators of the atrial substrate. This is logical, as these patients already exhibit the gross anatomic remodeling that LA size captures. Furthermore, a key secondary finding was that LAAPF velocity was the most robust predictor of LA/LAA clot (AUC, 0.953), significantly outperforming LA strain. This highlights a critical distinction: while LA strain assesses the function of the atrial wall (myopathy), LAAPF velocity directly measures blood flow dynamics within the appendage, which is the primary driver of stasis and thrombosis.<sup>13</sup>

The pathophysiological basis for these findings lies in the progression from atrial stretch and fibrosis to electrical instability.<sup>14</sup> While LA dimensions have traditionally tracked this anatomic remodeling,<sup>6,7</sup> LA strain offers a more direct assessment of myocardial function, which can precede gross anatomic changes.<sup>3,15</sup> Its validity as a reliable marker of atrial myopathy and interstitial fibrosis is established across various clinical scenarios, justifying its application in our high-risk cohort.<sup>16–27</sup> This functional assessment by LA strain is clinically vital, as predicting POAF is crucial due to its association with adverse outcomes, and LA strain has consequently emerged as a robust tool for this risk stratification.<sup>1,28</sup>

Furthermore, the utility of these functional and hemodynamic parameters extends beyond the initial prediction of POAF in surgery. LA strain is a well-established predictor of arrhythmia recurrence after interventions such as catheter ablation,<sup>29,30</sup> while a low LAAPF velocity is also related to recurrence and can be used to track thrombus resolution.<sup>31,32</sup> Our study is the first to apply these intraoperative TEE parameters to a high-risk cohort of patients with MS in NSR undergoing MVR, helping to establish reliable predictors in this specific population.

Our study has several key limitations. Primarily, we used LV-specific strain software (GE EchoPAC 204) as dedicated LA software was unavailable; although validated for LA use, dedicated software is recommended for better

reproducibility and consistency, representing a significant limitation.<sup>33</sup> Second, our analysis relied on intraoperative TEE, not the noninvasive gold standard of TTE. While we mitigated known TEE foreshortening issues by exclusively using the evidence-based deep transgastric view, these values are not interchangeable with TTE and may underestimate strain due to anesthetic effects and imaging angles, a finding consistent with prior validation studies.<sup>9</sup> Third, although, the care protocols were standardized, the surgical and anesthesiology providers participating in these cases varied, potentially introducing confounding. Fourth, the semiautomatic nature of the software required manual ROI tracking, which prevented blinding the echocardiographer to the patient's baseline rhythm and introduced potential bias. Finally, our study was limited to LA reservoir strain; a future analysis using dedicated software to assess all components of LA function could better determine which aspect of atrial myopathy is most critical in the genesis of AF.

## Conclusion

In conclusion, the optimal intraoperative echocardiographic assessment of the left atrium in patients with severe mitral stenosis should be multiparametric and tailored to the clinical question. LA reservoir strain is the most reliable tool for predicting new-onset postoperative atrial fibrillation in patients who are in sinus rhythm preoperatively, with a value less than 16.5% identifying patients at significantly higher risk. In contrast, LA dimensions are the echocardiographic parameters most strongly correlated with established, preexisting AF. For the distinct and critical risk of thrombosis, LA appendage flow velocity is the superior parameter. Clinicians should therefore employ this nuanced approach—using strain for functional assessment, size for anatomic remodeling, and appendage velocity for hemodynamics—to achieve a truly comprehensive perioperative risk stratification.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## CRedit authorship contribution statement

**Jijo Francis:** Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Neeti Makhija:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Formal analysis, Data curation, Conceptualization. **Arindam Choudhury:** Writing – review & editing, Validation, Methodology, Data curation. **Suruchi Hasija:** Writing – review & editing, Methodology, Conceptualization. **Sambhunath Das:** Writing – review & editing, Methodology, Conceptualization. **Minati Choudhury:** Writing – review & editing, Methodology, Conceptualization.

## Appendix: Calculation of the VIS

$$\begin{aligned} &10,000 \times \text{Vasopressin dose (U/kg/min)} + 100 \times \text{Epinephrine dose (mcg/kg/min)} + 100 \times \text{Norepinephrine dose (mcg/kg/min)} + 50 \times \text{Levosimendan dose (mcg/kg/min)} + 25 \times \text{Olprinone dose (mcg/kg/min)} + 20 \times \text{Methylene blue dose (mg/kg/h)} + 10 \times \text{Milrinone dose (mcg/kg/min)} + 10 \times \text{Phenylephrine dose (mcg/kg/min)} + 10 \times \text{Terlipressin dose (mcg/min)} + 0.25 \times \text{Angiotensin II dose (ng/kg/min)} + \text{Dobutamine dose (mcg/kg/min)} + \text{Dopamine dose (mcg/kg/min)} + \text{Enoximone dose (mcg/kg/min)} \end{aligned}$$

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