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Ultrasound assessment of the association between left atrial remodeling and fibrosis in patients with valvular atrial fibrillation: a clinical investigation

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Abstract

Background Advanced heart failure in patients with valvular atrial fibrillation (VAF) poses a significant threat to human health. Noninvasive assessment of left atrial remodeling in various pathological conditions is instrumental in guiding clinical treatment decisions, evaluating efficacy, and predicting prognosis.

Methods The study enrolled 63 patients diagnosed with mitral stenosis (MS), among whom 44 presented concomitant atrial fibrillation (AF) and 19 had sinus rhythm. Left atrial volume and functional parameters were evaluated using real-time three-dimensional echocardiography (RT-3DE) and two-dimensional speckle tracking imaging (2D-STI) techniques, while left atrial stiffness index (LASI) was calculated accordingly. During surgery, left atrial myocardial specimens were obtained to determine the CVF through histopathological evaluation, reflecting the extent of left atrial myocardial fibrosis. Comparative analysis was conducted between the AF group and the control group regarding left atrial volume, functional parameters, LASI, as well as their correlation with CVF.

Results (1) Patients with MS combined with AF exhibit larger left atrial volume, decreased strain at all stages, reduced function, and increased stiffness of the left atrium compared to patients in sinus rhythm. (2) LASI was positively correlated with CVF in both the control and AF groups, exhibiting the highest correlation coefficient ($p < 0.05$).

Conclusion The application of RT-3DE, 2D-STI, and LASI enables effective evaluation of left atrial structure and function changes in patients with VAF. LASI provides a more accurate indication of the extent of myocardial fibrosis.

Clinical trial number Not applicable.

Keywords Valvular atrial fibrillation, Myocardial fibrosis, Spot tracking, Non-invasive

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Introduction

The term “valvular atrial fibrillation” is used to describe patients who either have mitral valve stenosis or develop AF following artificial heart valve replacement surgery [1]. AF is the most frequent arrhythmia managed in clinical practice, and it is linked to an increased risk of death, stroke, and peripheral embolism [2, 3]. The prevalence of AF is increasing worldwide due to increased life expectancy and improved survival from other cardiovascular conditions [4, 5]. Among the global population of 15 million heart valve disease patients requiring surgical intervention, AF coexists in approximately 40% of MS cases and 75% of mitral regurgitation cases. In the pathophysiological progression of rheumatic MS, restricted opening of the mitral valve leads to elevated left atrial pressure as a consequence of hemodynamic changes, resulting in chronic stretching of the left atrium [6]. Prolonged stretching and stimulation of the atrium induce significant structural remodeling and functional impairment, characterized by cardiac enlargement and the presence of extensive areas with low voltage [7]. Myocardial cells surrounding the pulmonary veins exhibit prolonged effective refractory periods, leading to slowed conduction velocity and conduction block in cardiac electrical activity, ultimately culminating in AF. Moreover, even following successful valve replacement surgery, the incidence rate of AF remains as high as 60% [8]. Active elimination of AF and restoration of sinus rhythm in patients with AF can significantly reduce disability rates, improve long-term survival rates, and enhance quality of life [9]. For symptomatic patients, the combination of surgical treatment and catheter ablation for AF demonstrates favorable outcomes [10]. However, there still exist postoperative complications such as the recurrence of AF [11]. Previous studies have investigated the factors influencing the success rate of surgical ablation for VAF, wherein age and left atrial diameter (LAD) have been identified as independent predictors of postoperative recurrence [12]. Moreover, additional pertinent research has also corroborated that left atrial fibrosis contributes to atrial structural remodeling and serves as an autonomous predictor for post-ablation recurrence, stroke events, and progression of heart failure [13, 14]. Consequently, assessing fibrosis in patients with VAF has become a critical reference point for clinical decision-making and prognostic evaluation. This study aims to evaluate left atrial morphological parameters, functional metrics, and LASI in VAF patients utilizing real-time three-dimensional echocardiography alongside two-dimensional speckle tracking technology while systematically examining the relationships between these parameters and histopathological characteristics of left atrial myocardial fibrosis. The objective is to identify non-invasive imaging parameters that can indirectly reflect the extent of left atrial myocardial fibrosis.

Methods

Study population

The inclusion criteria comprised patients with MS who underwent mitral valve surgery at the Central People's Hospital of Yichang, Hubei Province, between October 2021 and October 2022. Patients were categorized into two groups based on the presence of AF: those with AF constituted the AF group, while individuals in sinus rhythm formed the control group. Following the established inclusion and exclusion criteria, a total of 63 patients were enrolled in this study, including 44 in the AF group and 19 in the control group. The inclusion criteria included: (1) patients diagnosed with rheumatic mitral valve disease who met indications for artificial valve replacement as per the 2014 AHA/ACC Guidelines for Management of Patients With Valvular Heart Disease [15]; (2) patients diagnosed with paroxysmal AF according to the 2020 European Society of Cardiology (ESC) Guidelines for Management of AF [16]; (3) patients who underwent valve replacement and/or radio-frequency catheter ablation via modified maze procedure under cardiopulmonary bypass. Exclusion criteria encompassed: (1) individuals with a history of coronary heart disease or congenital heart defects; (2) those who had received angiotensin II receptor blockers or angiotensin-converting enzyme inhibitors within six months prior to enrollment; (3) participants lacking complete clinical or pathological data as well as imaging records; and (4) subjects experiencing an episode of AF during echocardiographic assessment or whose images were deemed inadequate for analysis using 2D-STI and RT-3DE techniques. This study has received approval from our hospital's ethics committee (Ethics Approval Number:2021-107-01), and all participants provided written informed consent.

Clinical data

Upon admission, clinical baseline data—including gender, age, weight, height, BMI, and histories of hypertension and diabetes—were systematically collected and recorded. Additionally, the body surface area (BSA) of each patient was calculated to facilitate subsequent standardization of parameters.

Conventional echocardiographic measurements

Patients underwent transthoracic echocardiography using the Philips EPIQ7C color Doppler ultrasound imaging system (Philips, MA, USA) and X5-1 probe (1-3 MHz) within 24 hours prior to valve replacement surgery. The examination was performed with simultaneous connection to a chest lead electrocardiogram while the patient was in a resting left lateral decubitus position. All examinations and measurements were conducted according to the Adult Transthoracic Echocardiography Guidelines

established by the American Society of Echocardiography in 2018 [17]. LAD at end-systole was measured from endocardium to endocardium perpendicular to the aortic root in the parasternal long-axis view at the level of the sternum. Measurements of left ventricular end-diastolic diameter (LVDd), interventricular septum thickness (IVST), and left ventricular posterior wall thickness (LVPWT) were obtained in the apical four-chamber view at end-diastole. Left ventricular mass (LVM) was calculated using $LVM = 0.8 * 1.04 * [(IVST + LVPWT + LVDd)^3 - LVDd^3] + 0.6$ and standardized with BSA to obtain left ventricular mass index (LVMI). Left ventricular ejection fraction (LVEF) was measured using modified biplane Simpson's method. Tissue Doppler imaging in apical four-chamber view was used for measuring peak early diastolic mitral inflow velocity (E) and average peak early diastolic mitral annular velocity (e'), which were then utilized for calculating E/e' ratio.

Left atrium 2D-STI and RT-3DE analysis

Capture dynamic images of 3–5 cardiac cycles and save them in DICOM format for importing into the QLAB10.5 offline analysis workstation. Perform an analysis to derive peak longitudinal strain of the left atrium (PALS), conduit strain of the left atrium (LAScd), and contraction strain of the left atrium (LASct). Subsequently, compute LASI value using the formula $LASI = E/e' / PALS$ and record its average after three consecutive measurements. Use the QLAB10.5 offline analysis workstation for RT-3DE analysis. After importing the four-chamber cardiac cine images in DICOM format, select the 3DQ-Advanced module for processing and analysis. Obtain left atrial maximum volume index (LAVImax) and left atrial minimum volume index (LAVImin). Normalize these values to calculate left atrial volume functional parameters using the following formulas:

Left atrial maximum volume (LAVImax) = LAVmax / BSA;

Left atrial minimum volume (LAVImin) = LAVmin / BSA;

Left atrial ejection fraction (LAEF) = (LAVmax – LAVmin) / LAVmax * 100%;

Left atrial expansion index (LAEI) = (LAVmax – LAVmin) / LAVmin.

Histopathological analysis

In mitral valve replacement surgery, we collected left atrial myocardial specimens and prepared approximately 4 μ m thick paraffin sections of the entire myocardium after formaldehyde fixation. Subsequently, Masson's staining was performed followed by panoramic scanning. The obtained images were then scored and analyzed using Image-Pro plus 6.0 image analysis software to

quantify the CVF for assessing the extent of myocardial fibrosis.

Statistical analysis

The statistical analysis in this study was conducted using SPSS 25.0 software and GraphPad Prism 8.0 software. For normally distributed continuous data, the mean $\pm$ standard deviation ($\bar{x} \pm s$) was used to represent the data, while the median (M) and interquartile range (P25, P75) were used for non-normally distributed data. Categorical variables were presented as percentages. Independent sample t-test was employed to compare two groups of normally distributed continuous variables, while non-parametric tests were used for comparing non-normally distributed variables between two groups. Chi-square test or Fisher's exact probability method was utilized for intergroup comparisons of categorical variables. Spearman correlation test was applied to evaluate the correlation between left atrial ultrasound parameters and CVF. Results were considered statistically significant when $p < 0.05$ based on a two-tailed test.

Reproducibility test

Reproducibility test: Ten study subjects were randomly selected to assess the reproducibility of left atrial volume parameters, strain parameters, and CVF obtained through ultrasound measurements. Two different operators independently analyzed and measured the ultrasound parameters to compare the inter-observer reproducibility of these parameters. Multiple data measurements were performed during analysis to evaluate the intra-observer reproducibility of these parameters. Intra-class correlation coefficient (ICC) and Bland-Altman analysis were employed to assess the consistency of RT-3DE and 2D-STI software analysis parameters, as well as Image-Pro Plus 6.0 software measurement of CVF.

Result

Comparison of baseline clinical data

No statistically significant differences were observed in terms of age, gender, BMI, LVDd, LVMI, LVEF, and E/e' between the two groups based on statistical analysis results ($p < 0.05$). (Shown in Table 1).

Comparison of left atrial function, structural parameters, and LASI

In comparison to the control group, the AF group exhibited a significant increase in LAD, LAVImax, LAVImin, and LASI. Conversely, there was a significant decrease in LAEF, LAEI, and left atrial strain during different phases. These differences demonstrated statistical significance ($p < 0.05$). (Shown in Table 1).

Table 1 Comparison of clinical general data, left atrial structure and function parameters in patients

Variables	AF group	Control group	$\chi^2/z/t$	<i>p</i>
Age (y)	58.30 ± 8.56	53.63 ± 7.32	0.884	0.283
Gender (Man,%)	15 (34.1%)	9 (47.4%)	0.509	0.476
BMI	23.93 ± 3.30	22.73 ± 3.00	-1.409	0.164
LVDd (mm)	48.82 ± 7.38	52.47 ± 7.78	-1.775	0.081
LVMI (g/m ²)	83.84 (67.73,108.87)	104.44 (82.32,123.21)	-1.902	0.057
LVEF (%)	59.52 ± 8.12	61.37 ± 8.12	-0.826	0.414
E(cm/s)	167.5(122.5,199.5)	100.0(80.0,190.0)	-0.929	0.353
e'(cm/s)	5.78(4.49,6.96)	5.55(4.79,7.62)	-0.434	0.664
E/e'	30.92(16.86,41.59)	27.29(14.86,36.53)	-0.951	0.342
LAD(mm)	52.13(47.25,57.75)	43.12(41.45,48.56)	-3.614	<0.001
LAVImax	75.86(57.89,101.58)	47.53(38.78,56.94)	-3.444	0.001
LAVImin	57.89(41.16,77.46)	28.31(16.73,40.05)	-4.148	<0.001
LAEF(%)	26.65(18.43,32.60)	46.11(30.77,56.21)	-3.428	0.001
LAEI	0.37(0.23,0.48)	0.86(0.44,1.28)	-3.428	0.001
PALS	3.56(2.03,7.65)	15.80(8.91,29.91)	-4.486	<0.001
LAScd	-4.65(-4.65,-0.85)	-9.21(-16.40,-5.95)	-3.857	<0.001
LASct	-1.35(-2.90,0.33)	-6.01(-9.06,-2.80)	-4.111	<0.001
LASI	6.23(2.46,16.29)	1.44(0.55,3.32)	-3.789	<0.001

BMI: Body mass index; LVDd: Left ventricular diastolic diameter; LVMI: Left ventricular mass index; LVEF: Left ventricular ejection fraction; E: Peak early diastolic mitral inflow velocity; e': Average peak early diastolic mitral annular velocity; LAD: Left atrial diameter; LAVImax: Left atrial maximum volume; LAVImin: Left atrial minimum volume index; LAEF(%): Left atrial emptying fraction; LAEI: Left atrial expansion index; PALS: Peak longitudinal strain of the left atrium; LAScd: Left atrial strain during conduit phase; LASct: Left atrial strain during conduit phase; LASI: Left atrial stiffness index

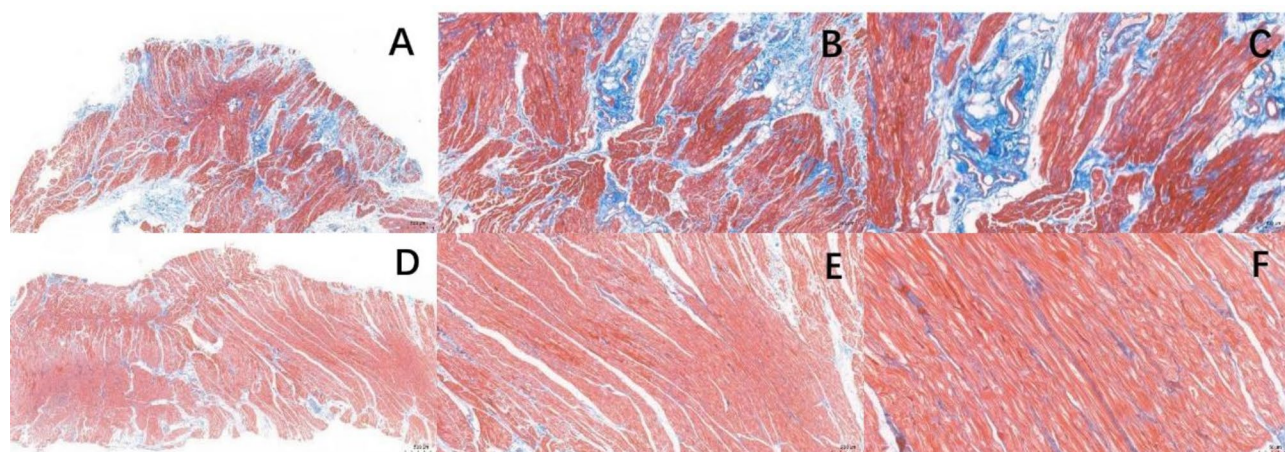


Fig. 1 Histological examination of myocardial tissue in patients. **A, B, C** show the myocardial tissue of a female patient, aged 62, with rheumatic mitral stenosis and AF under Masson staining. **D, E, F** show the myocardial tissue of a female patient, aged 60, with rheumatic mitral stenosis and sinus rhythm under Masson staining. **A, D:** Examine under a 2x magnifying glass; **B, E:** Examine under a 5x magnifying glass; **C, F:** Examine under a 10x magnifying glass

Histopathological assessment of myocardial fibrosis in the left atrium

Histopathological sections of the left atrial myocardial tissue revealed heterogeneous orientations of myocardial cells, stained red, with both cross-sectional and longitudinal arrangements. Meanwhile, fibrous collagen fibers appeared as blue stains, intertwining around the myocardial cells. In comparison to the control group, the AF group exhibited disorganized arrangement of myocardial cells and a broader distribution of collagen fibers primarily concentrated around blood vessels (Shown in Fig. 1). Conversely, in the control group, myocardial cells

demonstrated orderly arrangement with fewer distributed collagen fibers (Shown in Fig. 1).

Quantitative analysis on left atrial myocardial fibrosis

Quantitative analysis revealed a significant increase in the CVF within the left atrial myocardium of the AF group compared to the control group, with this difference being statistically significant ($p < 0.05$).

Relevance evaluation

A Spearman correlation analysis was conducted to investigate the association between left atrial structure and

Table 2 Correlation analysis of the structural and functional parameters of left atrial echocardiography with CVF

	AF group		Control group	
	SCC	<i>p</i>	SCC	<i>p</i>
LAD	0.216	0.163	0.455	0.051
LAVImax	0.312	0.040	0.335	0.161
LAVImin	0.381	0.011	0.500	0.029
LAEF	-0.283	0.063	-0.488	0.034
LAEI	-0.283	0.063	-0.488	0.034
PALS	-0.798	<0.001	-0.582	0.009
LAScd	0.539	<0.001	0.472	0.041
LASct	0.370	0.013	0.390	0.099
LASI	0.811	<0.001	0.589	0.008

LAD: Left atrial anteroposterior diameter; LAVImax: Maximum left atrial volume index; LAVImin: Minimum left atrial volume index; LAEF(%): Left atrial emptying fraction; LAEI: Left atrial expansion index; PALS: Peak longitudinal strain of the left atrium; LAScd: Strain during conduit phase of the left atrium; LASct: Strain during contraction phase of the left atrium; LASI: Left atrial stiffness index

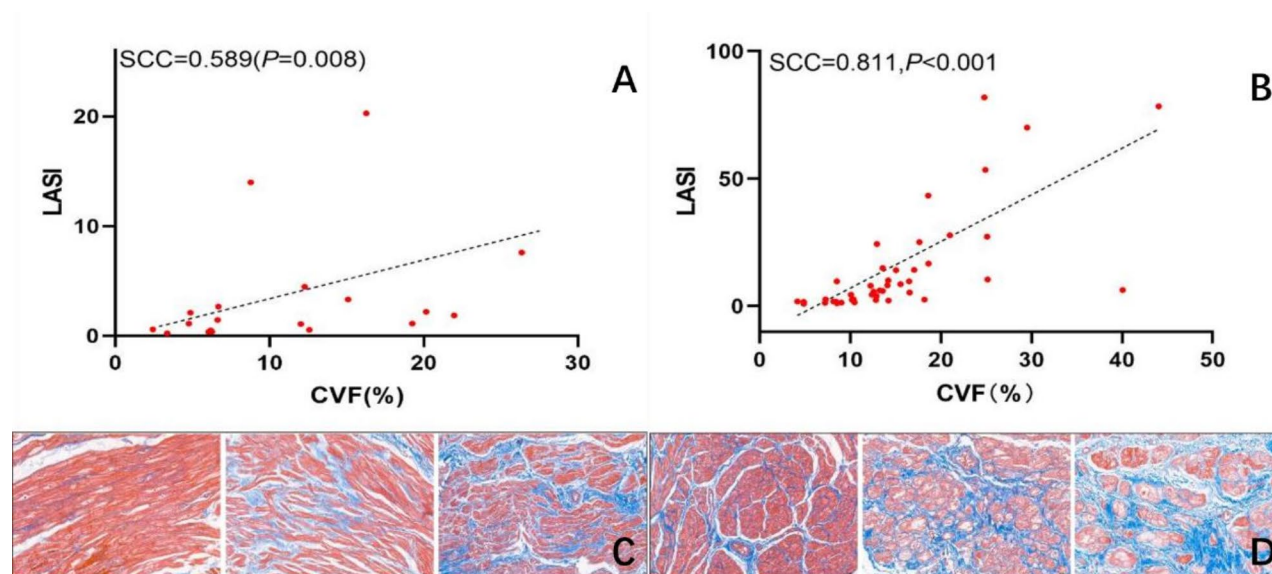


Fig. 2 Correlation between LASI and CVF. **A:** The LASI is positively correlated with CVF in the control group. **B:** The LASI is positively correlated with CVF in the AF group. **C:** From left to right are pathological sections of myocardial tissue from patients in the control group under a microscope. **D:** From left to right are pathological sections of myocardial tissue from patients in the AF group under a microscope

functional parameters, as well as CVF, in both the AF group and the control group (Shown in Table 2). The results revealed that in the AF group, LAVImax, LAVImin, LAScd, and LASct exhibited positive correlations with CV fibrosis, while PALS showed a negative correlation. No significant associations were observed between other parameters and CV fibrosis. In the control group, LAVImin and LAScd demonstrated positive correlations with CV fibrosis; however, LAEF, LAEI, and PALS displayed negative correlations. No significant relationships were found between other parameters and CV fibrosis. Furthermore, both the control group and the AF group exhibited a positive association with LASI; nevertheless, this association had a higher correlation coefficient in the AF group compared to the control group, indicating a statistically significant difference. (Shown in Fig. 2).

Discussion

Currently, VAF is limited to patients with MS or artificial heart valves who also have concomitant AF [1]. In comparison to non-VAF, patients with rheumatic heart disease and concomitant AF exhibit a higher mortality rate. The left atrium serves as a reliable indicator for assessing the severity of rheumatic heart valve disease, as well as the presence of volume and pressure overload. Changes in the geometric structure of the left atrium often correlate with an increased risk of adverse cardiac events [17, 18]. Therefore, an objective evaluation of left atrial remodeling can effectively determine the extent of myocardial damage in patients with VAF and offer valuable insights into their long-term prognosis. This study utilized RT-3DE and 2D-STI concurrently to assess the structure and function of the left atrium. RT-3DE enables tracking variations in left atrial volume throughout

different stages within a single cardiac cycle, thereby mitigating measurement errors arising from intricate chamber configurations encountered in 2D measurements [19]. On the other hand, 2D-STI allows for an independent evaluation of changes in left atrial myocardial function without being influenced by concurrent left ventricular dysfunction [20, 21]. Therefore, in this study, patients who had used ACEI or ARB medications within the preceding six months were excluded. ACEI and ARB have been shown to reduce the incidence of atrial fibrillation by modulating atrial remodeling. Consequently, they have become integral components in the primary prevention of atrial fibrillation. Post-radiofrequency ablation for atrial fibrillation, these drugs can further mitigate the recurrence of atrial fibrillation by inhibiting structural atrial remodeling [22].

In this study, patients with VAF exhibited significantly increased LAD, LAVImax, and LAVImin compared to patients with isolated MS. These findings are consistent with previous literature reports and further validate the impact of both AF and valve disease on left atrial remodeling [23–25]. Currently, there is a lack of research investigating the correlation between RT-3DE left atrial volume parameters and myocardial fibrosis histopathology in patients with VAF. In our study population with AF, both LAVImax and LAVImin exhibited a positive correlation with CVF, highlighting the potential of non-invasive measurement of myocardial fibrosis using LAVImax and LAVImin in individuals with VAF. In the control group consisting of individuals with MS, only LAVImin demonstrated a positive correlation with CVF, further confirming that an increase in end-diastolic volume of the left atrium due to fibrosis can be reflected by LAVImin. This study conducted a comparative analysis of left atrial strain in patients with VAF and isolated MS. The findings revealed a significant reduction in both LAEF and PALS among individuals with AF [26–28]. Correlation analysis demonstrated strong associations between left atrial strain at all phases and CVF in patients with AF, while only PALS and LAScd were found to be related to CVF in the control group. These results further support the notion that extensive fibrosis within the left atrium not only impairs reservoir and conduit function but also affects myocardial deformation during the booster pump phase, aligning with previous research findings [29]. The atrial emptying and expansion function of the AF group is not associated with CVF, whereas in the control group, LAEF and LAEI exhibit a negative correlation with CVF. This finding demonstrates that alterations in left atrial capacity occur earlier in patients with valvular heart disease affected by AF than functional changes resulting from myocardial collagen fiber deposition.

In the AF group, a positive correlation exists between LASct and CVF, while no significant correlation is

observed between LASct and CVF in the control group. This discrepancy may be attributed to atrial fibrosis affecting myocardial contraction during diastolic late auxiliary pump function in patients with VAF, whereas collagen deposition has not led to a reduction in auxiliary pump function among patients with sinus rhythm MS. These findings suggest that a decrease in left atrial strain occurs subsequent to the development of extensive myocardial fibrosis. In this study, both the AF group and the control group exhibited varying degrees of fibrosis in the atrial myocardium, unequivocally indicating that interstitial fibrosis precedes the onset of AF. Myocardial fibrosis induces cellular decoupling and separation of cardiac myocytes, resulting in atrial conduction blockage and heightened susceptibility to AF among patients with multiple sclerosis [30]. However, patients in the AF group displayed significantly higher CVF compared to those in the control group, confirming that AF further induces adaptive remodeling of the left atrium [31].

In recent years, the academic community has proposed employing the ratio of left atrial pressure to pulmonary artery wedge pressure as a parameter indicative of left atrial compliance, referred to as LASI. Compared to conventional indicators, LASI demonstrates enhanced accuracy and sensitivity by incorporating both left atrial perfusion pressure and myocardial strain. This comprehensive approach accurately reflects alterations in left atrial structure and function while mitigating potential confounding factors such as passive traction from adjacent myocardial tissue or cardiac motion [32]. Previous investigations have demonstrated the utility of LASI as a parameter for assessing left atrial function and monitoring changes in patients with AF [33, 34]. Additionally, an elevated LASI level is independently associated with increased risk of post-ablation recurrence of AF [33]. However, due to the invasive nature of measuring left atrial pressure, it has been discovered that employing non-invasive indicator E/e' as an alternative can effectively compensate for this limitation. This method is widely employed in clinical settings for calculating LASI and has garnered recognition from researchers both domestically and internationally [35–37]. The results of this study demonstrated a significant increase in LASI in the AF group compared to the control group, indicating impaired compliance and reduced myocardial elasticity. Previous studies have utilized MRI to quantitatively assess the association between left atrial fibrosis and ultrasound parameters [38]. However, limited research has directly analyzed the relationship between pathological fibrotic changes in myocardium and ultrasound parameters. In this study, we collected left atrial myocardial tissue from patients with AF and performed pathological analysis to quantify CVF, thereby evaluating the extent of myocardial fibrosis (Shown in Fig. 2).

We investigated the correlation between CVF and left atrial volume as well as functional parameters, revealing a significant positive association between LASI and CVF. Compared to strain and other ultrasound parameters assessing left atrial structure and function, LASI exhibited a stronger correlation with myocardial fibrosis. These findings suggest that LASI can indirectly reflect the degree of left atrial myocardial fibrosis and may serve as an assessment tool for evaluating left atrium remodeling.

Limitation

Firstly, this study is a single-center investigation with a limited number of cases. Thus, there is no universally applicable methodology to precisely determine the onset time of AF, and the impact of AF duration on changes in left atrial function in VAF remains uncertain.

Conclusion

The application of RT-3DE, 2D-STI, and LASI enables effective evaluation of left atrial structure and function changes in patients with VAF. Patients with MS combined with atrial fibrillation exhibit larger left atrial volume, decreased strain at all stages, reduced function, and increased stiffness of the left atrium compared to patients in sinus rhythm. Additionally, MS patients combined with atrial fibrillation demonstrate a higher degree of myocardial fibrosis, which can be better reflected by LASI.

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Author contributions

T.X. and H.H. wrote the main manuscript text. H.W. and Z.R. calculated data. L.X. and Z.A. analyzed data. Z.C. revised manuscript. All authors reviewed the manuscript.

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Data availability

The datasets generated and analysed during the current study are not publicly available due to patient privacy and scales copyright but are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

The study has been approved by the Ethics Committee of the First Clinical Medical Science College of China Three Gorges University & Yichang Central People's Hospital Ethics Committee, Ethics No. 2021-107-01. All subjects had signed informed consent forms.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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