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Left Atrial Reservoir Strain Across Atrial Fibrillation Phenotypes: A Case-Control Echocardiographic Study

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ABSTRACT:

Background: Atrial fibrillation (AF) is associated with progressive structural, electrical, and mechanical remodeling of the left atrium. Left atrial reservoir strain (LASr) and the PA-TDI interval have emerged as potential echocardiographic markers of atrial dysfunction and fibrosis. However, their relationships across different AF phenotypes and their incremental associations with conventional echocardiographic parameters require further evaluation.

Objective: To compare LASr among individuals with no AF (controls), paroxysmal AF, and persistent AF, and to determine whether differences remain after adjustment for clinical covariates, left atrial (LA) size, and derived LA emptying fraction. Secondary objectives were to assess the relationship between LASr and PA-TDI and explore the discriminatory performance of LASr using receiver operating characteristic (ROC) analysis.

Methods: This study evaluated LASr across three groups: controls, patients with paroxysmal AF, and patients with persistent AF. Comparative analyses were performed to examine differences in LASr among the groups, followed by adjusted analyses incorporating available clinical covariates and conventional echocardiographic measures of atrial remodeling. The association between LASr and PA-TDI was examined in participants with measurable PA-TDI values. Exploratory ROC analyses were conducted to assess the ability of LASr to distinguish between AF phenotypes and controls.

Conclusion: This study provides a comparative assessment of LASr across different AF phenotypes and examines its incremental association with clinical and conventional echocardiographic measures of atrial remodeling. The findings are intended to clarify the relationship between atrial mechanical dysfunction and AF progression while providing an exploratory evaluation of LASr and PA-TDI as echocardiographic markers. The results should be interpreted as replication and incremental-association evidence rather than as the discovery of a novel diagnostic marker.

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1. INTRODUCTION

Atrial fibrillation (AF) is the most common sustained cardiac arrhythmia encountered in clinical practice and is associated with an increased risk of stroke, heart failure, hospitalization, impaired quality of life, and all-cause mortality.[1] The prevalence of AF continues to increase with aging populations and the growing burden of cardiovascular risk factors, making early identification of atrial remodeling an important clinical objective. Despite advances in rhythm control strategies, AF remains a progressive disease characterized by structural, electrical, and mechanical remodeling of the left atrium, which contributes to both the initiation and maintenance of the arrhythmia.[2]

Left atrial fibrosis is considered a key substrate underlying atrial remodeling and AF progression[3,4]. Histopathological studies have demonstrated that progressive interstitial fibrosis disrupts atrial conduction, impairs atrial mechanical function, and promotes re-entry mechanisms that sustain AF[5,6]. Although cardiac magnetic resonance imaging with late gadolinium enhancement is regarded as the reference standard for non-invasive assessment of atrial fibrosis, its widespread clinical application is limited by cost, availability, technical complexity, and the need for specialized expertise. Consequently, there is considerable interest in identifying readily available echocardiographic markers that can reliably reflect the extent of atrial remodeling.

Speckle-tracking echocardiography has emerged as a valuable technique for assessing left atrial mechanics. Among its derived parameters, left atrial reservoir strain reflects atrial compliance and reservoir function and has been shown to correlate with atrial fibrosis, left atrial pressure, and adverse cardiovascular outcomes[7]. Similarly, total atrial conduction time measured by tissue Doppler imaging (PA-TDI interval) represents atrial electromechanical delay and has been associated with atrial fibrosis and the occurrence of AF.[8,9] These parameters provide complementary information regarding mechanical and electrical remodeling of the atrium and may identify atrial dysfunction before significant structural enlargement becomes apparent.

Although previous studies have demonstrated associations between left atrial strain, PA-TDI, and the presence of AF[10,11], comparatively few have evaluated these markers across different stages of AF progression while simultaneously examining their relationships with conventional echocardiographic measures of atrial remodeling. Furthermore, the independent diagnostic value of these parameters after adjustment for established cardiovascular risk factors remains incompletely defined.

Previous studies have already shown lower LASr across AF subtypes and associations between atrial electromechanical delay and paroxysmal AF. The present study should therefore be interpreted as a replication and incremental-association analysis rather than as a novel diagnostic discovery. Its primary objective was to compare LASr among controls, paroxysmal AF, and persistent AF and determine whether phenotype differences remained after adjustment for available clinical covariates, recorded LA size, and derived LA emptying fraction. Secondary objectives were to describe the relationship between LASr and PA-TDI when PA-TDI was measurable and to report explicitly exploratory, same-sample ROC analyses.

METHODS

Study design and participants

This was a case-control study with cross-sectional echocardiographic assessment. The analytic sample comprised 70 comparison participants without documented AF, 47 participants classified as having paroxysmal AF, and 23 classified as having persistent AF. Case or control status and AF phenotype were determined before the present statistical reanalysis. This design terminology is used because participants were selected by AF status and underwent a single echocardiographic assessment; the design does not estimate disease incidence or prospective risk. Subjects were recruited between October 2020 to October 2021 coming to Cardiology OPD. These were convenience sampling method.

Inclusion criteria:

Patients coming to Amrita Institute of medical sciences

Paroxysmal atrial fibrillation (holter/ECG proven) and Persistent atrial fibrillation

Exclusion Criteria:

Congenital heart disease

Valvular heart disease

Arrhythmias (other than AF)

Echocardiographic measurements

The available dataset contained LASr from the apical four-chamber view, PA-TDI, LA anteroposterior diameter, two LA size measurements, and left ventricular ejection fraction (LVEF). LASr was expressed as a positive percentage. PA-TDI was available in controls and participants with paroxysmal AF who were in sinus rhythm; it was not measured during persistent AF and was not imputed.

For the reanalysis, the smaller and larger recorded LA measurements were treated provisionally as minimum and maximum LA volumes, respectively, and total LA emptying fraction was calculated as (maximum−minimum)/maximum ×100. Chamber quantification should follow current echocardiographic recommendations.

LVEF values were converted to percentages; the single recorded range of 25–30% was represented by its midpoint (27.5%) for sensitivity analysis. All controls had LVEF recorded as 60%, indicating coarse measurement and limiting its interpretability.

Transthoracic echocardiography was performed using a standard phased-array cardiac transducer operating within a frequency range of approximately 1–5 MHz. Two-dimensional images for left atrial strain analysis were acquired at a frame rate of 50–90 frames/s. Left atrial reservoir strain was analysed offline. End-diastole, defined by onset of the QRS complex/R wave, was used as the zero-reference point. The LA endocardial border was manually traced in the apical four-chamber view, after which the software automatically generated the region of interest and tracking curve. Tracking quality was visually inspected and manually corrected when necessary. Segments with persistently inadequate tracking were excluded from the analysis.

PA-TDI was measured using pulsed-wave tissue Doppler imaging with the sample volume positioned at the lateral mitral annulus. Total atrial conduction time was defined as the interval from the onset of the P wave on the surface electrocardiogram to the peak of the A' wave at the tissue Doppler sampling site.

All echocardiographic measurements were performed by two observers. Formal intraobserver and interobserver reproducibility analyses were not performed, which should be considered a limitation of the study.

Clinical covariates

Available covariates were age, sex, hypertension, type 2 diabetes, dyslipidaemia, and prior cerebrovascular accident. One diabetes value was missing. BMI, LV mass or LV mass index, systematic heart-failure history, and complete CHA_2DS_2-VASc components were not available in the supplied master chart and were not reconstructed from free text.

Statistical analysis

Statistical analysis was performed using IBM SPSS Statistics version 31.0 (IBM Corp., Armonk, NY, USA) and JASP version 0.98.0. Continuous variables are summarized as mean ± standard deviation (SD), and categorical variables as n (%). Three-group continuous comparisons used Welch analysis of variance because group variances were not assumed equal; pairwise comparisons used Welch t tests with Holm adjustment. PA-TDI was compared between controls and paroxysmal AF using a Welch t test. LVEF used a Kruskal–Wallis test because the control group had zero recorded variance.

The primary adjusted analysis treated LASr as a continuous outcome. The model included indicators for paroxysmal and persistent AF (control reference), age per 10 years, sex, hypertension, diabetes, dyslipidaemia, prior cerebrovascular accident, the larger recorded LA measure per 5 units, and LA emptying fraction per 10 percentage points. Heteroskedasticity-consistent HC3 standard errors were used. Three phenotype contrasts were Holm-adjusted. Sensitivity models added LVEF and substituted LA diameter for the larger recorded LA measure.

An exploratory AF-status model used Firth bias-reduced logistic regression because no controls had hypertension, producing complete separation in ordinary maximum-likelihood regression. The prespecified model included the same clinical covariates, the larger recorded LA measure, LA emptying fraction, and LASr per 5-percentage-point decrease. The model describes association within the selected case-control sample and is not a risk-prediction model.

Exploratory ROC curves were calculated for LASr (AF versus control) and PA-TDI (paroxysmal AF versus control). AUC confidence intervals were obtained from 2,000 stratified bootstrap samples. Thresholds maximized Youden's index in the same observations used to assess accuracy and are therefore optimistic derivation-sample estimates. Two-sided $p<0.05$ was used.

Analyses were complete-case for adjusted models (n=139) and were performed in Python using SciPy and scikit-learn; the Firth model used the adjusted-score algorithm. The study is reported with reference to STROBE guidance.

Ethics

The Institutional Review Board (IRM-AIMS-2020-258) meeting was held on 15-09-2020 at 3pm.

Results

Participant characteristics

The study included 140 participants: 70 controls, 47 with paroxysmal AF, and 23 with persistent AF. Controls were substantially younger and none had hypertension, whereas hypertension was present in 61.7% of the paroxysmal group and 47.8% of the persistent group (Table 1). The pooled AF-group age recalculated from individual records was 66.97 ± 9.53 years.

Echocardiographic measures

Mean LASr decreased across control, paroxysmal AF, and persistent AF groups. The derived LA emptying fraction also differed overall, but its paroxysmal-versus-persistent comparison did not meet the Holm-adjusted 0.05 threshold (p=0.061). PA-TDI was longer in paroxysmal AF than controls (Table 2).

Adjusted LASr analysis

In the primary structural model, AF phenotype remained associated with LASr after adjustment for available clinical covariates, the larger recorded LA measure, and derived LA emptying fraction (adjusted R^2=0.664; Table 3). The Holm-adjusted persistent-versus-paroxysmal contrast was −4.51 percentage points (95% CI −8.11 to −0.90; p=0.015). Results were similar after adding LVEF (difference −4.66; 95% CI −8.40 to −0.91; Holm p=0.015) and when LA diameter replaced the larger recorded LA measure (−5.04; 95% CI −8.91 to −1.16; Holm p=0.011).

Firth regression for AF status

Firth regression retained hypertension without infinite estimates despite complete separation. Each 5-percentage-point lower LASr was associated with 3.16-fold higher odds of AF (95% CI 1.80–5.55; p<0.001) after adjustment for clinical covariates, the larger recorded LA measure, and LA emptying fraction (Table 4). The hypertension estimate was very imprecise (OR 66.05; 95% CI 2.97–1467.18), reflecting the absence of hypertensive controls rather than a stable effect estimate. Adding LVEF did not attenuate the LASr association (OR 4.04; 95% CI 1.97–8.26). In an age-overlap sensitivity subset (44–83 years; n=112), the LASr OR was 2.96 (95% CI 1.67–5.24).

PA-TDI and exploratory ROC analyses

Among the 117 participants with PA-TDI, LASr and PA-TDI were inversely correlated (r=-0.477; p<0.001). PA-TDI was not available in persistent AF, so no whole-spectrum model or imputation was performed.

DISCUSSION

Principal findings

LASr declined progressively from the control group to the paroxysmal and persistent AF groups. These between-group differences remained significant after adjustment for the available clinical covariates, the larger recorded LA area, and derived LA fractional area change. This finding indicates that LASr may reflect aspects of atrial mechanical dysfunction not fully captured by conventional measures of LA size and area change. However, the results should not be interpreted as evidence of an independent causal relationship between LASr and AF. The substantial differences in age and comorbidity burden between the study groups, particularly the absence of hypertension among controls, limit the clinical generalizability of the observed associations.

Reduced LASr in AF has been well documented and does not represent a novel observation. A large contemporary study similarly demonstrated lower LASr and LA emptying fraction and greater LA volumes across AF subtypes.[12] The present study contributes by evaluating LASr alongside recorded LA area, derived LA fractional area change, and PA-TDI within a local cohort, while incorporating the available structural and clinical covariates and using bias-reduced regression to address complete separation.

Mechanical function and conventional LA measurements

LA fractional area change and LASr both provide information regarding atrial mechanical function, whereas LA diameter and maximum LA area primarily characterize chamber size. Accordingly, LASr should not be considered the sole functional measure of the left atrium, and comparisons between LASr and measurements of chamber size should not be interpreted as direct assessments of relative superiority. In the unadjusted analyses, LA fractional area change differed between controls and both AF groups. However, the difference between the paroxysmal and persistent AF groups did not satisfy the Holm-adjusted threshold for statistical significance. In contrast, the difference in LASr between the two AF phenotypes remained significant after multivariable adjustment. These findings support an incremental association between LASr and AF phenotype in this cohort but do not establish that LASr is superior to, or can replace, conventional echocardiographic measurements.

The larger recorded LA area remained associated with LASr in the structural outcome model, whereas derived LA fractional area change did not. These findings require cautious interpretation because the available measurements represented LA areas in cm^2 rather than volumes, and neither body surface area nor LV mass was available for further adjustment. In addition, derived LA fractional area change is not equivalent to volumetric LA emptying fraction. Interpretation and reporting of these variables should therefore remain consistent with current recommendations for cardiac chamber quantification and deformation imaging.

Atrial electromechanical delay

PA-TDI was prolonged in participants with paroxysmal AF and demonstrated a moderate inverse correlation with LASr. The exploratory PA-TDI AUC of 0.830 is broadly consistent with previous evidence demonstrating prolonged tissue Doppler-derived atrial electromechanical delay in paroxysmal AF. Nevertheless, the present control group was younger and had a substantially lower comorbidity burden than the paroxysmal AF group, with no hypertension recorded among controls. Consequently, the observed discriminative performance of PA-TDI is likely to be overestimated. Furthermore, because PA-TDI was not assessed during ongoing persistent AF, its performance cannot be generalized across the full spectrum of AF phenotypes.

AF-status model and ROC analysis

Firth bias-reduced logistic regression permitted hypertension to remain in the model despite complete separation and demonstrated that lower LASr was associated with AF status after adjustment for the available clinical covariates, the larger recorded LA area, and derived LA fractional area change. However, penalized regression addresses numerical instability and does not correct the underlying absence of clinical overlap between the study groups. The markedly imprecise estimate for hypertension, reflected by its wide confidence interval, indicates that the model cannot reliably disentangle the association of AF from the effects of hypertension, age, and related comorbidities.

The LASr AUC of 0.952 primarily reflects discrimination between selected younger, non-hypertensive controls and older participants with a greater comorbidity burden and established AF. It should not be interpreted as evidence that LASr can discriminate AF with comparable accuracy in an age- and comorbidity-matched clinical population. Moreover, the LASr threshold of ≤22.5% was selected and evaluated using the same 140 participants. The corresponding sensitivity of 82.9% and specificity of 95.7% therefore represent optimistic derivation-sample estimates and may be substantially lower in an independent cohort. In view of the same-sample threshold selection, the absence of matched controls, and recognized intervendor variability in LASr measurements, this threshold should not be applied to diagnosis, screening, ablation selection, or other clinical decisions without prospective external validation in appropriately matched populations.

Clinical interpretation

These results do not show that a low LASr value should alter management in a patient with sinus rhythm or established AF. At present, LASr should be regarded as a research measure of atrial phenotype and interpreted together with LA area, fractional area change, cardiac rhythm, and the broader clinical context. Prospective studies in age- and comorbidity-matched populations are required to determine whether LASr adds reproducible prognostic information beyond established clinical and echocardiographic variables and whether management based on that information improves outcomes. Any proposed relationship between reduced LASr and AF progression, rhythm-control success, or procedural outcomes remains hypothesis-generating because these outcomes were not evaluated in the present cross-sectional study.

LIMITATIONS

This single-centre case-control study with cross-sectional echocardiographic assessment was modest in size and cannot establish temporal or causal relationships. Controls were substantially younger than participants with AF, and none had hypertension. Although Firth regression addressed the numerical problem of complete separation, it could not correct the underlying absence of clinical overlap between the groups. Consequently, the observed discrimination should not be interpreted as expected diagnostic performance in an unselected clinical population.

BMI, body surface area, volumetric or indexed LA measurements, LV mass, systematic heart-failure history, and complete CHA_2DS_2-VASc components were unavailable. The dataset contained LA areas in cm^2 rather than LA volumes, so adjustment for volumetric LA size was not possible. LVEF was coarsely recorded, with all controls assigned a value of 60%, and one diabetes value was missing. Recruitment, eligibility, image acquisition, analysis software, blinding, and reproducibility details must be completed from the source documentation. The cardiac-cycle timing of the two recorded LA areas also requires confirmation, and the derived fractional area change is valid only if the larger and smaller measurements represent the maximum and minimum LA areas, respectively.

PA-TDI was unavailable by design during persistent AF, and no imputation was attempted. Cardiac magnetic resonance, histology, or electroanatomic mapping was not performed, so the echocardiographic measures cannot be interpreted as direct measures of fibrosis.[12] No prospective AF progression, treatment response, ablation outcome, or clinical utility was assessed. Finally, the ROC cut-offs were selected and evaluated in the same sample and therefore require prospective external validation before any clinical application.

CONCLUSIONS

LASr was lower across AF phenotypes and remained associated with phenotype and AF status after adjustment for available clinical covariates, recorded LA size, and derived LA emptying fraction. PA-TDI was longer in paroxysmal AF when measurable. Because the controls were unmatched and no controls had hypertension, the findings should be interpreted as exploratory cross-sectional associations. The internally derived LASr and PA-TDI thresholds are not ready for clinical use.

DECLARATIONS

Ethics approval and consent

The study protocol was approved by the Institutional Review Board of Amrita Institute of Medical Sciences at its meeting held on 15 September 2020. The study was conducted in accordance with the principles of the Declaration of Helsinki. Informed consent was obtained from all participants before their inclusion in the study.

CRediT author contributions

Vijay Nagappa: Conceptualization, Methodology, Investigation, Data curation, Formal analysis, Visualization, Project administration, Supervision, Writing—original draft, and Writing—review and editing.

Shamantha M C: Software, Formal Analysis, Validation, and Writing—review and editing.

Vijay Nagappa is the corresponding author. Both authors reviewed and approved the final manuscript and accept responsibility for the integrity and accuracy of the work.

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Conflicts of interest

None

Data availability

The de-identified data supporting the findings of this study are available from the corresponding author upon reasonable request, subject to approval by the Institutional Review Board of Amrita Institute of Medical Sciences and applicable institutional data-sharing policies. The data are not publicly available because they contain information that could compromise participant privacy and confidentiality.

Use of generative AI

During preparation of this revision, the authors used ChatGPT (OpenAI) for language editing, manuscript organization, and assistance in preparing a statistical reanalysis workflow. The authors reviewed the output, verified analyses and references against source material, and accept full responsibility for the manuscript. Adapt this disclosure to the target journal's current policy.

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Table 1. Clinical characteristics of participants according to atrial fibrillation phenotype

Characteristic	Control (n=70)	Paroxysmal AF (n=47)	Persistent AF (n=23)
Age, years	48.11 ± 14.16	65.66 ± 9.37	69.65 ± 9.54
Male sex	42 (60.0)	36 (76.6)	16 (69.6)
Hypertension	0 (0.0)	29 (61.7)	11 (47.8)

Type 2 diabetes	8 (11.6)	18 (38.3)	7 (30.4)
Dyslipidaemia	8 (11.4)	21 (44.7)	8 (34.8)
Prior CVA	0 (0.0)	3 (6.4)	2 (8.7)

Footnotes: Values are presented as mean ± standard deviation or number (percentage). Percentages were calculated within each phenotype group. Type 2 diabetes data were available for 69 control participants because one value was missing. AF, atrial fibrillation; CVA, cerebrovascular accident; SD, standard deviation.

Table 2. Echocardiographic characteristics according to atrial fibrillation phenotype

Measure	Control	Paroxysmal AF	Persistent AF	p value
LASr (%)	32.57 ± 7.40	16.95 ± 7.67	10.69 ± 5.60	<0.001
PA-TDI (s)	0.096 ± 0.018	0.131 ± 0.032	—	<0.001
LA diameter (cm)	3.30 ± 0.37	4.00 ± 0.63	4.36 ± 0.54	<0.001
Provisional LAVmin*	7.65 ± 2.54	11.37 ± 4.13	14.70 ± 6.21	<0.001
Provisional LAVmax*	13.12 ± 3.12	16.29 ± 4.28	19.47 ± 7.49	<0.001
Derived LAEF (%)*	42.02 ± 12.67	30.53 ± 15.11	24.74 ± 10.01	<0.001
LVEF (%)†	60.00 ± 0.00	54.99 ± 10.65	56.35 ± 8.35	<0.001

Footnotes: Values are presented as mean ± standard deviation. Overall p values were calculated using Welch analysis of variance, except for PA-TDI, which was compared between the control and paroxysmal AF groups using Welch's t test, and LVEF, which was compared using the Kruskal–Wallis test. PA-TDI was available only for controls and participants with paroxysmal AF (n=117). The labels LAVmin and LAVmax are provisional pending confirmation of the measurement type, units, and cardiac-cycle timing in the source records. LAEF was calculated as (LAVmax − LAVmin)/LAVmax × 100 and is valid only if the source measurements represent true minimum and maximum LA volumes. All control participants had an LVEF recorded as 60%. AF, atrial fibrillation; LA, left atrial; LAEF, left atrial emptying fraction; LASr, left atrial reservoir strain; LAVmax, maximum left atrial volume; LAVmin, minimum left atrial volume; LVEF, left ventricular ejection fraction; PA-TDI, tissue Doppler–derived atrial electromechanical delay.

Table 3. Multivariable linear regression analysis of factors associated with left atrial reservoir strain

Term	B	HC3 SE	95% CI	p value
Paroxysmal AF	-11.51	1.92	-15.32 to -7.70	<0.001
Persistent AF	-16.02	2.12	-20.21 to -11.83	<0.001
Age (per 10 years)	-0.08	0.49	-1.04 to 0.89	0.877
Male sex	-1.63	1.32	-4.24 to 0.99	0.221
Hypertension	-0.36	1.95	-4.23 to 3.50	0.854
Diabetes	-2.00	1.51	-4.99 to 0.99	0.188
Dyslipidaemia	-1.46	1.60	-4.62 to 1.70	0.361
Prior CVA	2.72	4.96	-7.09 to 12.53	0.584
Larger recorded LA volume (per 5 mL)	-2.95	0.72	-4.38 to -1.51	<0.001
LA emptying fraction (per 10 points)	0.65	0.42	-0.18 to 1.48	0.121

Footnote: The analysis included 139 participants with complete data. LASr was the dependent variable. Control participants constituted the reference phenotype. B represents the adjusted mean difference for categorical variables and the adjusted regression slope for continuous variables. Age was modelled per 10-year increase, the larger recorded LA measurement per 5-unit increase, and LAEF per 10-percentage-point increase. Heteroskedasticity-consistent HC3 standard errors were used. P values for phenotype contrasts were adjusted using the Holm method; all other p values were unadjusted. Model R^2=0.688; adjusted R^2=0.664. AF, atrial fibrillation; CI, confidence interval; CVA, cerebrovascular accident; HC3, heteroskedasticity-consistent standard error; LA, left atrial; LAEF, left atrial emptying fraction; LASr, left atrial reservoir strain; SE, standard error.

Table 4. Firth bias-reduced logistic regression analysis of factors associated with atrial fibrillation status

Term	Adjusted OR	95% CI	p value
Age (per 10 years)	2.29	1.13 to 4.63	0.021
Male sex	0.74	0.13 to 4.27	0.732
Hypertension	66.05	2.97 to 1467.18	0.008
Diabetes	0.81	0.12 to 5.47	0.826
Dyslipidaemia	0.41	0.07 to 2.42	0.326
Prior CVA	0.65	0.00 to 86.81	0.865
Larger recorded LA volume (per 5 mL)	1.84	0.59 to 5.75	0.292
LA emptying fraction (per 10 points)	0.75	0.41 to 1.38	0.356
LA reservoir strain (per 5-point decrease)	3.16	1.80 to 5.55	<0.001

Footnotes: The analysis included 139 participants with complete data. The outcome was AF status, with control status as the reference. Firth bias-reduced logistic regression was used because hypertension completely separated participants with AF from controls. Age was modelled per 10-year increase, the larger recorded LA measurement per 5-unit increase, LAEF per 10-percentage-point increase, and LASr per 5-percentage-point decrease. Odds ratios describe associations within this selected case-control sample and should not be interpreted as estimates of prospective risk. AF, atrial fibrillation; CI, confidence interval; CVA, cerebrovascular accident; LA, left atrial; LAEF, left atrial emptying fraction; LASr, left atrial reservoir strain; OR, odds ratio.

Table 5. Exploratory same-sample discrimination of left atrial reservoir strain and PA-TDI for atrial fibrillation

Marker	Comparison	AUC	Bootstrap 95% CI	Cut-off*	Sensitivity	Specificity
LASr	AF vs control	0.952	0.917–0.979	≤22.5%	82.9%	95.7%
PA-TDI	Paroxysmal AF vs control	0.830	0.743–0.906	≥0.12 s	72.3%	85.7%

Footnote: The LASr analysis compared all participants with AF against controls (n=140); the PA-TDI analysis compared participants with paroxysmal AF against controls (n=117). Confidence intervals for AUCs were obtained from 2,000 stratified bootstrap samples. Cut-offs were selected by maximizing Youden's index in the same participants used to assess performance and therefore represent unvalidated, potentially optimistic estimates. LASr thresholds of ≤22.5% and ≤22.0% produce identical classifications in this dataset because no observed value lies between these values. AF, atrial fibrillation; AUC, area under the curve; CI, confidence interval; LASr, left atrial reservoir strain; PA-TDI, tissue Doppler–derived atrial electromechanical delay.

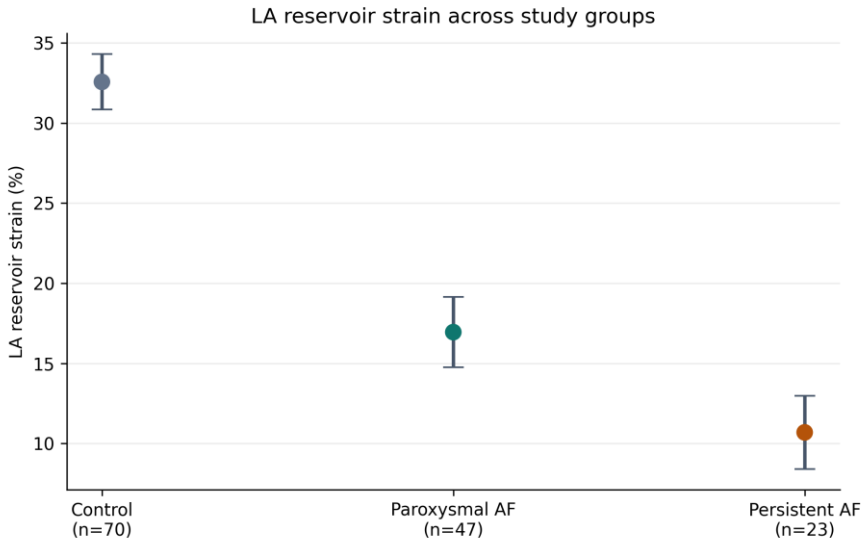


Figure 1. Unadjusted mean left atrial reservoir strain according to atrial fibrillation phenotype

Footnote: Mean LASr is shown for controls (n=70), participants with paroxysmal AF (n=47), and participants with persistent AF (n=23). Error bars represent 95% confidence intervals. This descriptive comparison is unadjusted and does not account for differences in age, hypertension, or other clinical characteristics among the groups. AF, atrial fibrillation; LASr, left atrial reservoir strain.

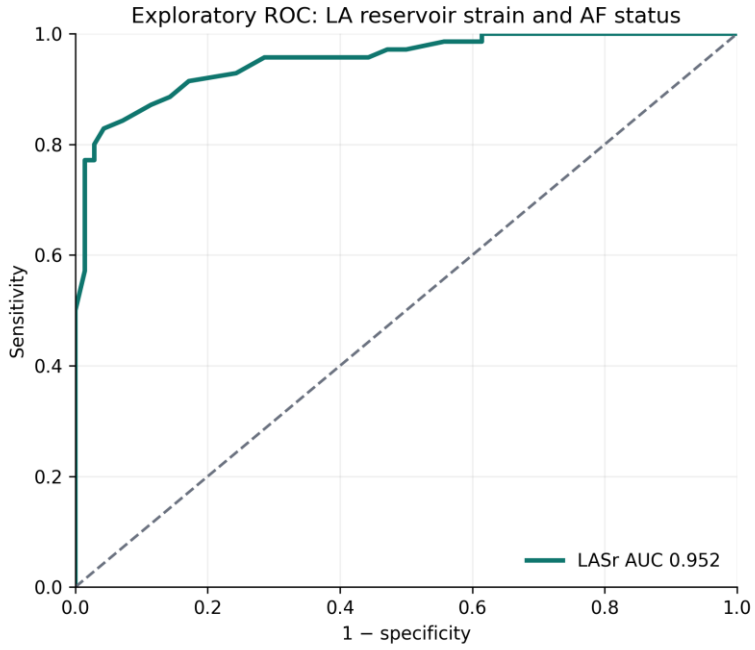


Figure 2. Exploratory receiver operating characteristic curve of left atrial reservoir strain for atrial fibrillation status

Footnote: The curve evaluates LASr for distinguishing participants with AF from controls in the selected case-control sample (n=140). Lower LASr values indicate a greater likelihood of AF. The AUC was 0.952 (bootstrap 95% CI, 0.917–0.979). The internally derived threshold of LASr ≤22.5% provided 82.9% sensitivity and 95.7% specificity. The threshold and performance estimates were derived and evaluated in the same sample and have not been externally validated. AF, atrial fibrillation; AUC, area under the curve; CI, confidence interval; LASr, left atrial reservoir strain; ROC, receiver operating characteristic.