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Article

Predictive Value of an Atrial Fibrillation Burden-Based Model for Early Recurrence After Circumferential Pulmonary Vein Ablation for Paroxysmal Atrial Fibrillation

Liping Wang[1], Xiu Feng[1], Jinmei Gao[1], Huilin Ren[1], Yuxia Miao[1], Peixuan Zhao[2], Min Xu[1,]*

[1]Department of Echocardiography and Cardiology, The Third Affiliated Hospital of Soochow University, 213003 Changzhou, Jiangsu, China
[2]Department of Cardiology, The Third Affiliated Hospital of Soochow University, 213003 Changzhou, Jiangsu, China
*Correspondence: loisicelin@163.com (Min Xu)

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Abstract

Background: To explore the importance of a predictive model, we combined the proportion of time in atrial fibrillation (AF) recorded by 24-hour dynamic electrocardiogram (DCG) with left ventricular function data. This study evaluated the probability of premature recurrence following circumferential pulmonary vein ablation (CPVA) in individuals with paroxysmal atrial fibrillation (PAF). **Methods**: A total of 237 PAF patients who were scheduled to undergo the first CPVA were selected, and the following patient data were collected: (1) Transthoracic echocardiographic assessment of left ventricular ejection fraction (LVEF) using the biplane Simpson technique; (2) Atrial fibrillation burden parameters obtained by 24-hour DCG, including the total time of AF, number of AF arrays, and proportion of time in AF; (3) Based on DCG findings obtained 3–6 months post-procedure, participants were categorized into either the sinus rhythm cohort or the recurrence cohort. Multivariate logistic regression analysis was subsequently performed to identify significant predictors influencing PAF recurrence following CPVA intervention; (4) An integrated forecasting framework was developed, with predictive capabilities evaluated through receiver operating characteristic (ROC) curve assessments to determine model efficacy. **Results**: (1) Among 224 participants undergoing CPVA for PAF, follow-up assessments at 3–6 months identified 20 cases (8.9%) with arrhythmia recurrence. Comparative analysis revealed elevated values for brain natriuretic peptide (BNP), left ventricular diastolic dimension (LVDD), SDNN Index (representing two R waves, RR interval variability), and atrial fibrillation burden in the recurrence cohort versus those maintaining sinus rhythm (all $p < 0.05$). Conversely, the recurrence group demonstrated reduced LVEF, minimum heart rate (MinHR), maximun heart rate (MaxHR), and minute meter slowest heart rate compared to the rhythm-controlled population (all $p < 0.05$). (2) Multivariate logistic regression analysis showed that BNP, MaxHR, and proportion of time in AF were independent influencing factors for PAF recurrence (all $p < 0.05$). (3) An integrated forecasting framework incorporating biomarkers including BNP, LVEF, and atrial fibrillation burden metrics was developed. Receiver operating characteristic analysis demonstrated superior predictive capability for the composite model (area under the curve, AUC = 0.874) when compared to atrial fibrillation burden assessment alone (AUC = 0.744) (p = 0.014). **Conclusion**: The proportion of time in AF combined with LVEF has good predictive value for early recurrence in PAF patients after CPVA.

Keywords

atrial fibrillation; circumferential pulmonary vein ablation; proportion of time in AF; left ventricular ejection fraction; early recurrence

Introduction

Atrial fibrillation (AF) stands as one of the prevalent arrhythmias encountered in clinical settings, characterized by significant morbidity and mortality rates. This condition can compromise patients' cardiac function, potentially resulting in heart failure (HF), Brain-related conditions such as cognitive deterioration and dementia, cardiovascular emergencies including heart attacks and abrupt cardiac arrest, along with increased risk of death from any cause, thereby diminishing the overall quality of patients' lives [1]. The 2020 European Society of Cardiology (ESC) guidelines have upgraded catheter ablation to a class I recommendation for drug-refractory paroxysmal atrial fibrillation (PAF) [2,3]. However, despite the continuous progress of circumferential pulmonary vein ablation (CPVA) technology and the reduced risk of postoperative recurrence compared to before, the recurrence rate reported in relevant literature remains relatively high [4]. Some risk prediction strategies have shown some correlations with the outcomes of AF ablation, but the current AF guidelines do not recommend their use in selecting patients for AF ablation, possibly due to their moderate efficacy.

Previous studies have often classified patients with AF as either paroxysmal or non-paroxysmal. This binary assessment modalities often lack the assessment of AF burden. Dynamic electrocardiogram (DCG) can dynamically observe the changes in electrocardiogram, and can evaluate AF burden indicators such as the onset time, extended periods of AF, frequency of episodes, and percentage of time spent in arrhythmia. This provides a quantitative evaluation and analysis of AF burden. The American College of Cardiology (ACC) indicates that, in comparison to PAF, persistent AF has seen a 60% increase in the incidence of HF, and prognosis differs significantly among patients with varying AF burdens. As the AF burden rises, so does the risk of stroke, HF, and death [5,6]. A greater proportion of time in AF corresponds to a longer duration of AF. Consequently, this metric objectively assesses the burden of AF or the efficacy of pharmacological therapy.

Previous research on PAF patients has primarily centered on the left atrium [7], while investigations into left ventricular function remain sparse. CPVA can improve left ventricular systolic and diastolic function in AF patients. The pathophysiological process of AF patients is closely related to ventricular fibrosis, which increases with the duration of AF [8]. Previous studies have confirmed that AF can induce left ventricular systolic dysfunction through tachycardia-mediated cardiomyopathy, leading to ventricular fibrosis and even HF [9]. It is crucial to recognize that numerous risk factors linked to AF also play a role in its progression, recurrence after ablation, and related complications [10]. Simultaneously, examining left ventricular structural and functional alterations aids in evaluating the onset, persistence, and advancement of AF.

With the advancement in scientific comprehension regarding atrial fibrillation, our investigation specifically examines the phenomenon of post-ablation recurrence in individuals diagnosed with PAF. Initially, we sought to determine the threshold of AF burden linked to postoperative recurrence. Following this, we constructed a recurrence risk prediction model by integrating factors such as LVEF and other relevant parameters. Ultimately, this study aims to aid in optimizing the invasive rhythm control strategy for PAF patients, enabling the most informed decisions.

Materials and Methods

Subjects

A retrospective analysis was performed on the clinical data of 237 patients hospitalized in the Department of Cardiology at Changzhou First People's Hospital (The Third Affiliated Hospital of Soochow University). These patients, comprising 137 males and 100 females, were admitted between January 2021 and December 2022 and were scheduled to undergo their first CPVA operation. Inclusion criteria: (1) AF lasting no more than 7 days, spontaneous termination of AF, and confirmed PAF by electrocardiogram and 24-hour DCG; (2) no documented evidence of structural cardiac conditions including atherosclerotic cardiovascular disorders or inherited cardiac abnormalities; (3) The patient exhibited no clinical manifestations of heart failure, with echocardiographic findings prior to surgery showing normal cardiac function without any indications of impaired myocardial performance; (4) no liver or kidney insufficiency; (5) no respiratory disease; and (6) clinical symptoms of AF. All patients had taken more than one antiarrhythmic drug. The patient selection process is shown in Fig. 1.

Image Acquisition and Analysis

(1) Echocardiography: All patients underwent transthoracic echocardiography 3 days before CPVA. The Philips Epic 7C color Doppler ultrasound system was employed for diagnostic assessment. Participants assumed a left lateral decubitus position while maintaining rest, with continuous 12-lead electrocardiogram monitoring. Cardiac imaging utilized the X5-1 transducer operating at 1–5 MHz frequency, capturing approximately 50 frames per second. Parasternal and apical views were acquired in both M-mode and two-dimensional formats. Cardiac dimensions including left atrial dimension (LAD), left ventricular diastolic dimension (LVDD) were recorded, with left ventricular ejection fraction (LVEF) calculated through biplane Simpson's technique. Two doctors with seniority or above continuously collected five cardiac cycles and took the average value. All the echocardiographic images of the patients were digitally stored.

(2) 24-hour DCG : All patients completed the examination within 3 days before the operation. The BI9100 type 24-hour DCG produced by Shenzhen Boying Medical Instrument Technology Co., Ltd. was used for the examination. The patients were in a supine position, and 75% alcohol cotton balls were used to wipe the skin of the examination area. After the skin dried, the electrode patches were adhered to the left and right sides of the clavicles and the costal arches, the intersection point of the clavicle midline, and the chest leads electrode was installed at the conventional 12-lead electrocardiogram V1 to V6 lead positions. Ensure that the quality of the electrocardiogram signals of each lead is good, then start and continuously record the 12-lead dynamic electrocardiogram. Instruct patients to refrain from strenuous activities and avoid excessive fatigue. Following a 24-hour period, image recordings were finalized and subsequently imported and archived. The collected electrocardiogram data underwent cross-analysis by at least two experienced attending physicians. It's important to note that the doctors reviewing and analyzing the electrocardiograms were blinded to the operation results. The evaluation of continuous cardiac monitoring data in-

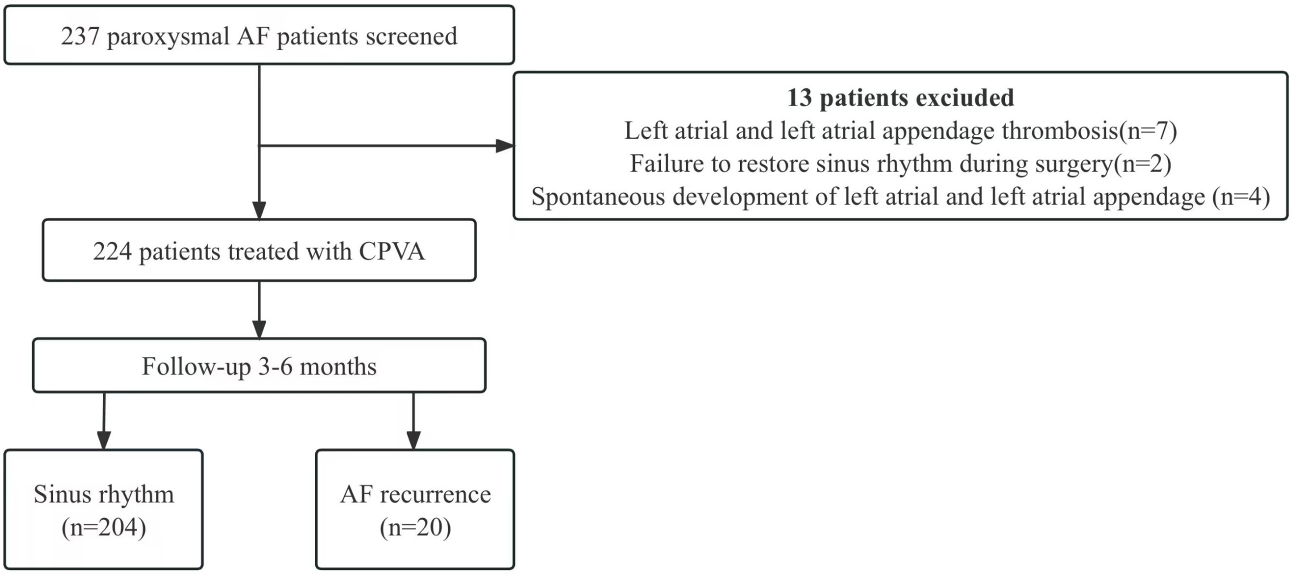

Fig. 1. Flowchart of patients selection. AF, atrial fibrillation; CPVA, circumferential pulmonary vein ablation.

corporated multiple atrial fibrillation metrics, including cumulative AF duration, episode frequency, and percentage of time spent in arrhythmia. Inter-rater reliability assessments were performed on a subset of 20 cases, demonstrating strong agreement intraclass correlation coefficient, ICC = 0.915; 95% confidence interval (95% CI) 0.798–0.965).

Percutaneous Catheter Radiofrequency Ablation

The left femoral vein was punctured. A decapolar catheter was positioned within the coronary sinus (CS) through the right femoral venous access. Dual transseptal punctures were performed via the same venous approach, facilitating the introduction of both a circular pulmonary vein mapping catheter and an irrigated ablation catheter. The procedure employed a three-dimensional electroanatomic mapping platform (CARTO system, Biosense Webster, Inc., Irvine, CA, USA) for both the creation and verification of radiofrequency ablation lesions, and computed tomography was employed to optimize the 3D reconstruction of the pulmonary veins and left atrium. The radiofrequency energy was delivered via a cooled-tip catheter with a diameter of 3.5 millimeters (Biosense, Webster, Inc., Irvine, CA, USA) incorporating temperature monitoring. Power output remained fixed at 40 watts, with tissue temperatures typically maintained below 34 °C while administering saline irrigation at 25 milliliters per minute during pulmonary vein isolation procedures. Creating electrical isolation between the left atrium and pulmonary vasculature required circumferential ablation around corresponding veins until myocardial potentials diminished below 0.15 millivolts and venous potentials were completely abolished. In the presence of regular atrial tachycardia or atrial flutter, further mapping and linear ablation of the critical isthmus are required [11]. The end point of surgery was complete isolation of the pulmonary vein potential.

Postoperative Management, Follow-up and Grouping

Every participant had been prescribed novel oral anticoagulant medications (non-vitamin K antagonist anticoagulants, NOACs) for at least 60 days postoperatively, and they had taken antiarrhythmic medications for 3 months prior. The electrocardiogram was monitored daily for 3 days following the surgery. Following discharge, the patients' 24-hour DCG were reviewed monthly, and a system for follow-up via telephone and fax to collect DCG data was established. All patients were followed up for 3–6 months, and antiarrhythmic drugs and anticoagulant drugs were adjusted according to the follow-up results. Criteria for determining the recurrence of PAF [12]: Atrial tachyarrhythmias lasting 30 s or more, confirmed by electrocardiogram or DCG, occurred at 3 months after CPVA.

Statistical Analysis

All statistical analysis were performed using R version 3.4.3 (https://www.R-project.org). Quantitative variables demonstrating normal distribution characteristics were presented as mean values accompanied by standard deviation measurements ($\bar{x} \pm s$). Measurement values exhibiting non-normal distribution patterns were presented using median values accompanied by interquartile ranges [M (P_{25}, P_{75})]. The t tests or Mann–Whitney U tests were used for comparisons between groups. Due to the moderately positively skewed distribution of total time of AF, number of AF arrays, and proportion of time in AF, the statistics were performed after natural log transformation. The experimental results were presented as mean values ± standard deviation (SD). Categorical variables were described using frequency counts (percentages), with intergroup comparisons conducted through chi-square analysis or Fisher's exact test when appropriate.

The predictive framework was constructed employing multinomial logistic regression analysis, with model optimization achieved through minimization of the Akaike information criterion (AIC). For internal validation procedures, we implemented the bootstrap sampling approach (500 iterations) as outlined in the TRIPOD guidelines [13]. All predictive models underwent receiver operator characteristic (ROC) curve reconstruction. Comparative assessment of diagnostic accuracy and AUC values across various models was conducted following the statistical methodology described by DeLong *et al*. [14]. Statistical significance thresholds were maintained at p-values below 0.05.

Result

Basic Data Comparison Between the Recurrence Group and the Sinus Rhythm Group

All patients underwent trans-esophageal echocardiography prior to surgery. Seven patients were unable to undergo CPVA because of thrombosis, 2 patients did not convert to sinus rhythm during the procedure, and 4 patients were ineligible for CPVA due to spontaneous contrast in the left atrium or left atrial appendage. In conclusion, the study encompassed 224 PAF patients effectively treated with CPVA, consisting of 129 males and 95 females, all of whom achieved sinus rhythm restoration during the procedure. A total of 224 participants underwent postoperative monitoring spanning 3 to 6 months. Based on DCG assessments, individuals with PAF were categorized into two cohorts: those experiencing recurrence (n = 20, 8.9%) and those maintaining sinus rhythm (n = 204). Comparative analysis of clinical parameters, serum brain natriuretic peptide (BNP) concentrations, echocardiographic measurements, and Holter-derived metrics revealed significant intergroup differences (Table 1). Post-ablation evaluation demonstrated elevated levels of BNP, LVDD, mean of the standard deviation of normal RR intervals (SDNN Index), and logarithmic transformation of atrial fibrillation burden in the recurrence cohort relative to the sinus rhythm group (all $p < 0.05$). In contrast, this group showed reduced LVEF, minimum heart rate (MinHR), maximum heart rate (MaxHR), and minute meter slowest heart rate (all $p < 0.05$).

Binary Multivariate Logistic Regression Analysis of Independent Influencing Factors of AF Recurrence

Logistic regression models were employed to analyze the impact of BMI, BNP, LVEF, MaxHR, and the proportion of time in AF on the recurrence of AF (Table 2). The findings revealed that BNP, MaxHR, and the proportion of time in AF were significant independent predictors of recurrence following CPVA in patients with PAF (all $p < 0.05$).

ROC Curve Analysis of the Value of Univariate and Combined Models in Predicting AF Recurrence

In this study, we conducted a univariate ROC curve analysis on several parameters, including the proportion of time in AF, LVEF, BNP, and MaxHR (Table 3, Fig. 2A). The results showed that the AUC and its 95% CI were 0.744 (0.631–0.856), 0.734 (0.627–0.841), 0.717 (0.596–0.839), and 0.673 (0.532–0.760), respectively. The diagnostic efficiency of proportion of time in AF was the best (AUC = 0.744).

A combined model for assessing AF burden was developed, and the equation was $\text{Logit (P)} = 5.238 + 0.153 \times \text{BMI} + 0.003 \times \text{BNP} - 0.094 \times \text{LVEF} - 0.076 \times \text{MaxHR} + 0.065 \times$ proportion of time in AF. The diagnostic accuracy of both the optimal univariate AF duration ratio and the composite predictive algorithm was evaluated through receiver operating characteristic analysis (Table 3, Fig. 2B). Comparative assessment revealed superior predictive capability of the integrated AF burden framework over the isolated temporal AF measurement for anticipating post-CPVA relapse in paroxysmal AF cases (area under curve values: 0.874 versus 0.744), with this disparity reaching statistical significance ($p = 0.014$).

Builded the Nomogram for the Prediction of AF Recurrence With the Combined Model of AF Burden

The nomogram for predicting AF recurrence, based on the combined model of AF burden, was constructed (Fig. 3). The nomogram offers a direct representation of the quantified scores, the cumulative total, and the associated risks for each factor. Additionally, it enables the computation of predicted values for individual outcome events. Based on an individual patient's BMI, BNP level, LVEF, MaxHR, and the proportion of time in AF, specific scores are assigned. Using these scores, the nomogram then allows us to determine the probability of AF recurrence. Decision curve analysis (DCA) verified that the combined prediction model accurately identified patients experiencing recurrence of AF following CPVA surgery. Within predicted probability thresholds ranging from 0% to 65%, the prognostic model demonstrated a favorable net benefit (Fig. 4A). The calibration curve further exhibited excellent concordance between the model's predicted and actual observed values (Fig. 4B).

Discussion

This research developed an integrated forecasting system incorporating the atrial fibrillation load metric obtained through electrocardiography along with systolic per-

Table 1. Basic information of PAF patients (N = 224).

	Total (n = 224)	Sinus rhythm (n = 204)	AF recurrence (n = 20)	p-value
Age (years)	61.500 ± 9.210	61.505 ± 9.191	61.450 ± 9.644	0.980
Male, n (%)	129 (57.589%)	118 (57.843%)	11 (55.000%)	0.806
BMI (kg/m^2)	24.569 ± 3.352	24.492 ± 3.240	25.348 ± 4.359	0.277
Smoking, n (%)	49 (21.875%)	46 (22.549%)	3 (15.000%)	0.436
Hypertension, n (%)	135 (60.268%)	125 (61.275%)	10 (50.000%)	0.325
Diabetes mellitus, n (%)	25 (11.161%)	22 (10.784%)	3 (15.000%)	0.568
Hyperlipidemia, n (%)	36 (16.071%)	33 (16.176%)	3 (15.000%)	0.891
Stroke, n (%)	2 (0.892%)	2 (0.980%)	0 (0.000%)	0.132
CHA2DS2-VASc score	1.504 ± 1.071	1.505 ± 1.094	1.500 ± 0.827	0.940
TC (mmol/L)	4.138 ± 0.985	4.133 ± 1.001	4.196 ± 0.821	0.787
TG (mmol/L)	1.874 ± 1.532	1.899 ± 1.590	1.627 ± 0.705	0.451
HDL-C (mmol/L)	1.036 ± 0.271	1.039 ± 0.275	1.013 ± 0.230	0.688
LDL-C (mmol/L)	2.253 ± 0.801	2.243 ± 0.814	2.350 ± 0.661	0.570
APOA1 (g/L)	1.105 ± 0.229	1.111 ± 0.234	1.038 ± 0.166	0.176
APOB (g/L)	0.793 ± 0.276	0.792 ± 0.277	0.809 ± 0.280	0.788
BNP (pg/mL)	149.500 (68.925–423.625)	138.600 (63.925–377.300)	432.350 (140.225–609.475)	<0.001*
IVS (mm)	9.099 ± 1.452	9.119 ± 1.388	8.900 ± 2.024	0.521
LAD (mm)	39.342 ± 5.813	39.168 ± 5.781	41.100 ± 5.990	0.157
LAVI (mL/m^2)	36.609 ± 6.981	36.648 ± 6.941	36.210 ± 7.555	0.790
RA (mm)	34.444 ± 14.082	34.354 ± 14.257	35.361 ± 12.417	0.761
LVDD (mm)	48.977 ± 4.714	48.718 ± 4.439	51.600 ± 6.484	0.009*
LVEF (%)	61.338 ± 5.053	61.851 ± 4.049	56.150 ± 9.615	<0.001*
Mitral regurgitation				0.673
No, n (%)	170 (75.892%)	155 (75.980%)	15 (75.000%)	
Mild, n (%)	49 (21.875%)	45 (22.059%)	4 (20.000%)	
Moderate and above, n (%)	5 (2.232%)	4 (1.961%)	1 (5.000%)	
Tricuspid regurgitation				0.323
No, n (%)	183 (81.696%)	167 (81.863%)	16 (80.000%)	
Mild, n (%)	38 (16.964%)	35 (17.157%)	3 (15.000%)	
Moderate and above, n (%)	3 (1.339%)	2 (0.980%)	1 (5.000%)	
Mean heart rate (bpm)	72.857 ± 11.061	73.270 ± 11.185	68.650 ± 8.875	0.075
MinHR (bpm)	59.196 ± 9.728	59.672 ± 9.688	54.350 ± 8.987	0.019*
MaxHR (bpm)	98.138 ± 18.788	98.892 ± 19.255	90.450 ± 10.655	0.032*
Minute meter slowest heart rate (bpm)	61.598 ± 9.955	62.029 ± 10.037	57.200 ± 8.037	0.038*
Minute meter fastest heart rate (bpm)	94.103 ± 15.336	94.681 ± 15.734	88.200 ± 8.685	0.071
HF (ms^2)	62.800 (23.900–187.800)	56.800 (21.900–151.175)	248.700 (110.900–300.000)	0.799
LF (ms^2)	56.000 (21.600–175.000)	53.450 (21.200–151.200)	198.900 (81.700–247.750)	0.965
SDNN Index (ms)	27.000 (17.000–40.000)	23.000 (16.000–37.000)	43.000 (30.500–47.000)	0.002*
Triangle index	14.665 ± 6.483	14.495 ± 6.464	16.474 ± 6.577	0.204
Ln[Total time of AF (mins)]	5.186 ± 1.584	5.066 ± 1.860	5.407 ± 0.913	0.556
Ln[Number of AF arrays (n)]	2.257 ± 1.724	1.909 ± 1.883	2.896 ± 1.209	0.112
Ln[Proportion of time in AF (%)]	2.519 ± 1.584	2.009 ± 1.422	3.019 ± 1.064	0.003*
Antiarrhythmic drugs				0.889
Amiodarone, n (%)	31 (15.196%)	28 (13.725%)	3 (15.000%)	
Propafenone, n (%)	19 (9.314%)	18 (8.824%)	1 (5.000%)	
Sotalol, n (%)	13 (6.373%)	12 (5.882%)	1 (5.000%)	
β-blockers, n (%)	102 (50.000%)	96 (47.059%)	6 (30.000%)	

Abbreviations: BMI, body mass index; TC, total blood cholesterol; TG, triacylglycerides; HDL-C, high-density lipoprotein cholesterol; LDL-C, low-density lipoprotein cholesterol; APOA1, apolipoprotein A-I; APOB, apolipoprotein B; BNP, brain natriuretic peptide; IVS, ventricular septal thickness; LAD, left atrial dimension; LAVI, left atrial volume index; RA, right atrial size; LVDD, left ventricular diastolic diameter; LVEF, left ventricular ejection fraction; MinHR, minimum heart rate; MaxHR, maximum heart rate; Minute meter slowest heart rate, the minimum cardiac rhythm observed per minute; Minute meter fastest slowest heart rate, the maximum cardiac rhythm observed per minute; HF, high-frequency spectral power; LF, low-frequency spectral power; SDNN Index, mean of the standard deviation of normal RR intervals; * means $p < 0.05$.

Table 2. Binary multivariate logistic regression analysis of influencing factors of postoperative recurrence in PAF patients.

Variables	Estimate	Std error	OR	95% CI	*p*-value
BMI	0.153	0.080	1.165	0.996–1.363	0.056
BNP	0.003	0.001	1.003	1.000–1.006	0.026
LVEF	–0.094	0.053	0.911	0.820–1.011	0.080
MaxHR	–0.076	0.024	0.927	0.883–0.972	0.002
Proportion of time in AF	0.065	0.019	1.067	1.028–1.108	0.001

Abbreviations: BMI, body mass index; BNP, brain natriuretic peptide; LVEF, left ventricular ejection fraction; MaxHR, maximum heart rate.

Table 3. ROC curve to evaluate the predictive effect of univariate and predictive models on AF recurrence.

Variable	AUC (95% CI)	Cut-off value	Specificity	Sensitivity	Accuracy
Ln[Proportion of time in AF]	0.744 (0.631–0.856)	2.1910	0.912	0.600	0.884
LVEF	0.734 (0.627–0.841)	60.500	0.678	0.800	0.689
BNP	0.717 (0.596–0.839)	135.200	0.495	0.900	0.531
MaxHR	0.673 (0.532–0.760)	90.500	0.672	0.650	0.670
Model	0.874 (0.800–0.948)	0.2194	0.946	0.700	0.923

Abbreviations: LVEF, left ventricular ejection fraction; BNP, brain natriuretic peptide; MaxHR, maximum heart rate.

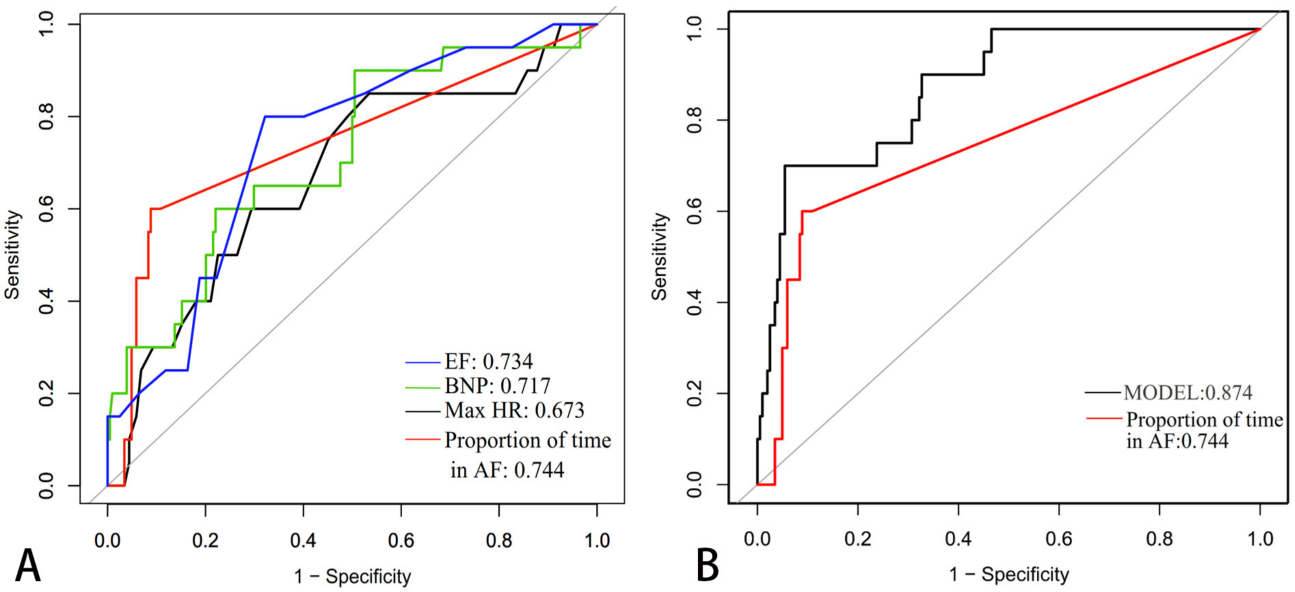

Fig. 2. ROC curve of univariate and MODEL prediction of AF recurrence. (A) ROC curve of univariate prediction of AF recurrence. The blue line represents EF prediction value of AF recurrence, the green line represents BNP prediction value of AF recurrence, the black line represents MaxHR prediction value of AF recurrence and the red line represents proportion of time in AF prediction value of AF recurrence. (B) ROC curve of proportion of time in AF and combined model for predicting AF recurrence. The black line represents model prediction value of AF recurrence, the red line represents proportion of time in AF prediction value of AF recurrence. Abbreviations: EF, ejection fraction; BNP, brain natriuretic peptide; MaxHR, maximum heart rate; AF, atrial fibrillation.

formance measurements of the left ventricle from cardiac ultrasound imaging. This model exhibits high specificity and accuracy, making it suitable for predicting recurrence after CPVA in patients with PAF.

Catheter ablation has emerged as an indispensable treatment option for AF, with numerous clinical studies attesting to the effectiveness and safety of CPVA. This approach has been shown to markedly alleviate patients' symptoms and enhance their overall quality of life [15]. Meta-analyses demonstrate that, when compared to drug rhythm control alone, radiofrequency ablation significantly reduces the rate of readmission and cardioversion for AF patients, while also decreasing the HF symptom score [16, 17]. Although ablation offers certain benefits, these are frequently counterbalanced by the recurrence of AF, making the accurate prediction of postoperative recurrence a signif-

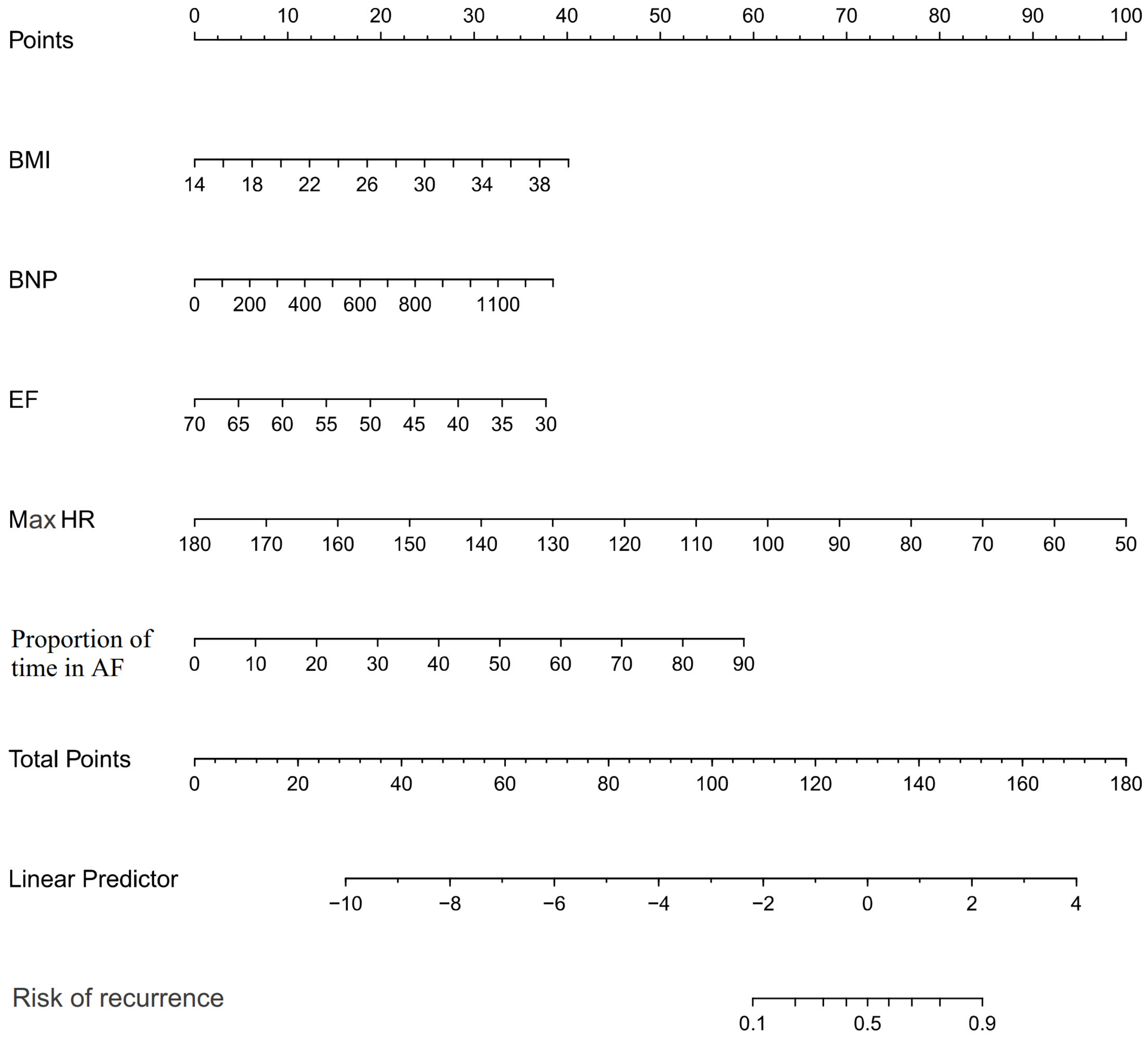

Fig. 3. Prognostic nomogram integrating atrial fibrillation burden for predicting arrhythmia recurrence.

icant clinical hurdle. Consequently, the ability to pinpoint patients at elevated risk of AF recurrence following CPVA via noninvasive markers is crucial for clinicians to devise superior treatment strategies and enhance clinical decision-making.

The precise biological processes contributing to atrial fibrillation recurrence following surgical intervention remain incompletely elucidated. Evaluating the likelihood of AF reoccurrence post-ablation through examination of fundamental biomarker measurements represents a viable clinical approach. These measurable parameters offer convenient detection methods while yielding clinically significant predictive data [18]. The burden of atrial fibrillation (AF) is closely linked to cardiovascular outcomes, and recent progress in monitoring methods has enabled a more precise assessment of how AF burden evolves and its significance in clinical settings [5]. Several scholars have investigated the association between heart rate and the occurrence or recurrence of atrial fibrillation, revealing that an excessively low heart rate may elevate the risk of atrial fibrillation as well as its recurrence following surgery. For instance, O'Neal and colleagues' research findings [19] show that a drop in resting heart rate correlates with a heightened AF risk. This observation remains consistent among diverse subgroups categorized by age, gender, race, and the existence of coronary atherosclerotic heart disease. Moreover, further studies have uncovered a complex connection between a decrease in resting heart rate and the function of the autonomic nervous system (ANS) [20], which is pivotal in controlling AF persistence [21]. Elevated ANS activity reduces the action potential duration by augmenting acetylcholine-dependent potassium current and concurrently stimulates calcium transients via increased norepinephrine release [22]. These processes combined elevate

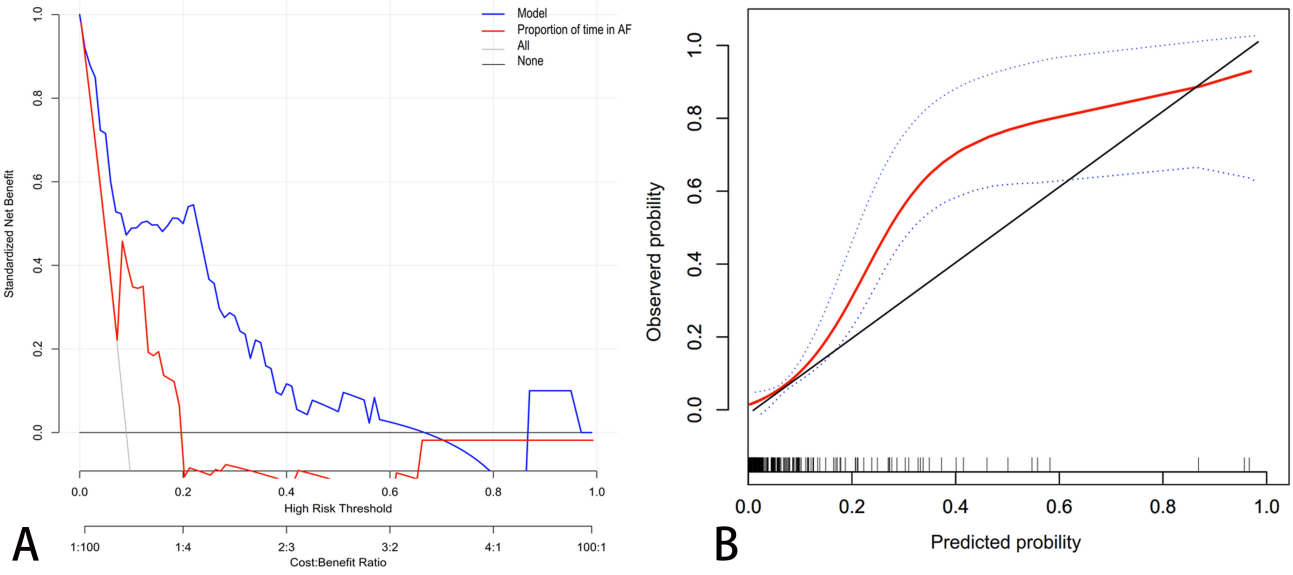

Fig. 4. Decision curve and Calibration curve of prediction model. (A) Decision curve of prediction model. Analysis of decision curves for predicting AF recurrence in PAF patients following CPVA. The composite prediction model's net benefit curve is presented alongside individual factor analysis. The black solid line represents the scenario where no PAF patients experience AF recurrence post-CPVA, while the grey solid line depicts the assumption that all patients develop recurrent AF. Optimal model selection depends on identifying superior net benefit across all potential threshold values. (B) Calibration curve of prediction model. Calibration curve of the combined model of AF burden for predicting AF recurrence. The x-axis displays projected occurrence rates, while the y-axis represents documented AF recurrence frequencies. A solid black reference line denotes perfect alignment between projections and observations. The calibration trend appears in red, with light blue shading marking the 95% confidence interval boundaries for all predictive estimates.

early afterdepolarization potentials, thus aiding the production of AF trigger potentials and upping the frequency of AF recurrences [23]. Studies demonstrate that patients who spend a greater proportion of time in AF experience significantly elevated rates of AF recurrence and increased AF burden following ablation, compared to those with shorter AF durations [24]. Chew *et al*. [25]. demonstrated a significant independent link between elevated atrial fibrillation (AF) burden and increased risks of mortality from any cause, hospital admissions for various conditions, and ischemic stroke events, following a clear dose-response pattern. Whether quantifying AF burden through temporal percentage measurements or assessing the longest continuous AF episode duration, researchers observed remarkably similar prognostic implications across both metrics. After adjusting for multiple variables, permanent AF exhibited stronger associations with heart failure development than paroxysmal AF did, indicating that as AF burden increases, so does the risk of HF [5]. The investigation revealed that patients experiencing recurrent atrial fibrillation spent significantly more time in AF post-ablation than those maintaining sinus rhythm. This temporal disparity proved to be an autonomous indicator of AF recurrence following circumferential pulmonary vein ablation. The rhythm monitoring data showed distinct patterns between the cohorts, with the recurrence group displaying prolonged arrhythmic episodes that correlated strongly with subsequent AF reoccurrence ($p = 0.001$). Additionally, the proportion of time in AF proved moderately effective (AUC = 0.744) as a univariate indicator for predicting recurrence after radiofrequency treatment. Hence, clinicians may be able to enhance the treatment strategies and prognostic outcomes for patients undergoing catheter-based radiofrequency ablation [26].

Echocardiography, a simple and noninvasive diagnostic procedure, is extensively employed to evaluate cardiac structure and function. Atrial fibrillation triggers significant alterations in both electrical conduction patterns and tissue architecture within the cardiac chambers, playing a pivotal role in sustaining and advancing abnormal heart rhythms [27]. Significantly, structural changes in the atria have been linked to reduced effectiveness of circumferential pulmonary vein ablation (CPVA) for atrial fibrillation (AF) treatment [28]. Research indicates that enlarged left atrial (LA) dimensions serve as a predictive marker for AF reoccurrence post-CPVA. Berruezo and colleagues [29] demonstrated this correlation through their investigation of 148 participants and revealed that increased anterior-posterior left atrial dimension was associated with higher likelihood of atrial fibrillation recurrence after circumferential pulmonary vein ablation. Individuals presenting with significant left atrial dilation were clearly identifiable as belonging to the “elevated recurrence probability” group, whereas patients demonstrating mild or moderate atrial enlargement displayed inconsistent therapeutic outcomes following the ablation procedure. Consequently, numerous studies have sought to identify additional predictive parameters for the success of CPVA in treating AF. The assessment of left ventricular volume and LVEF holds significant importance in the management of AF patients. AF can exacerbate symptomatic HF through multiple pathophysiological mechanisms, including the uncoordinated movement of the atriums and ventricles characteristic of this condition. Elevated ventricular pacing rates coupled with diminished atrial contraction efficiency may result in heightened diastolic pressure within the left ventricle alongside compromised systemic blood flow [30], showing decreased LVEF, promotes ventricular muscle remodelling and increases the risk of HF [31]. Additionally, impaired left ventricular function in individuals with atrial fibrillation contributes to further atrial dilation, worsening left atrial structural changes and hastening AF progression. This study employed the two-dimensional biplane Simpson's method to assess LVEF. The findings revealed that patients who experienced recurrence following radiofrequency ablation had lower LVEF prior to surgery. This suggests that impaired left ventricular systolic function may be associated with permanent structural changes in the left atrium. These alterations could promote the progression from paroxysmal to chronic atrial fibrillation while increasing the likelihood of post-ablation AF recurrence. Toplisek *et al.* [32] examined the correlation between AF burden and atrioventricular remodelling by prospectively tracking 37 AF patients over a 12-month period. AF burden was evaluated using a cardiac electronic implant device, whereas atrioventricular remodelling and atrioventricular function recovery were determined through echocardiography. Their findings revealed that patients with a lower AF burden exhibited more pronounced reverse remodelling of the left atrium, accompanied by a more significant enhancement in left ventricular systolic function. The CASTLE-AF study has established that radiofrequency ablation, while unable to fully cure AF, effectively limits ventricular rate by decreasing AF burden. This reduction subsequently enhances cardiac output, reverses ventricular remodelling, and improves patients' cardiac function. Furthermore, AF burden may possess predictive value regarding long-term cardiac function [33].

Researchers have repeatedly explored and optimized tools for predicting recurrence after radiofrequency ablation [34,35], some of which have advantages, but these tools need to be developed without increasing the medical burden on patients and society. DCG and echocardiography are both preoperative routine evaluation indicators for AF patients. The combination of multiple indicators is a multidimensional evaluation of AF patients, which is conducive to accurate prediction of the prognosis of patients. Knecht *et al.* [36] have shown that the single index P wave prolongation time is a good predictor. When integrated with structural measurements of the left atrium, this composite indicator demonstrates superior capability in forecasting atrial fibrillation recurrence following CPVA procedures. Within the spectrum of left atrial structural metrics, solely the volume index exhibited comparable predictive value, while remaining parameters showed negligible association with clinical outcomes or arrhythmia burden. Our research developed an innovative predictive framework for anticipating early postoperative AF recurrence, which incorporates AF duration percentages alongside standard clinical markers like left ventricular ejection fraction, substantially improving both diagnostic precision and discriminatory power. Furthermore, a nomogram for predicting AF recurrence based on the combined model of atrial fibrillation burden was drawn. The complex regression equation was transformed into a visual graph, making the results of the model more readable and facilitating the assessment of patient prognosis. As in this study, when the patient's BMI = 27 kg/m^2 (20 points), BNP = 500 pg/mL (15 points), LVEF = 60% (10 points), MaxHR = 108 bpm (55 points), and the proportion of time in AF = 61% (40 points), the total score is 140 points. From the nomogram, it can be seen that the risk of recurrence of atrial fibrillation is about 71%.

This study still has certain limitations. Due to the difference in ventricular filling time and the influence of heart rate, even if the measurement data of PAF patients are averaged after multiple cardiac cycles, there may be some bias. The heart rate of the patients after ablation cannot be recorded continuously for a long time because the implantable cardiac monitors (ICM) [37] not used, sporadic AF episodes might go undocumented, making it challenging to accurately assess the long-term clinical outcomes for patients following ablation procedures. Given that the use of beta-blockers may substantially influence the measurement of MaxHR, in future studies, we intend to incorporate corrections for additional confounding factors to further enhance the predictive capability of the model. Given the limited number of participants, we refrained from separating them into distinct modeling and validation cohorts. Instead, statistical reliability was assessed through bootstrap-based internal validation techniques. Consequently, expanding the participant pool remains essential for refining the predictive model's parameters.

Conclusion

The model created using DCG to derive the AF burden index, when combined with the left ventricular systolic function index, exhibits high accuracy and specificity in predicting early recurrence of PAF following radiofrequency ablation. It can be used to identify high-risk patients with AF recurrence at early stage, inform patients of the risk-benefit ratio, help doctors optimize patient selection, and implement personalized treatment plans.

Availability of Data and Materials

The data that support the findings of this study are available on request from the corresponding author.

Author Contributions

LPW and MX participated in research design, data analysis and interpretation, and writing of the manuscript; XF, MX and PXZ participated in sample collection, and contributed to the acquisition, interpretation of data and writing some of the manuscript; JMG, MX, and HLR participated in the acquisition of electrocardiogram and echocardiography images as well as partial manuscript writing; MX and YXM participated in research design, supervised the course of the project, and revised the manuscript. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

This study adhered to the guidelines outlined in the revised 2013 Helsinki Declaration, and informed consent was obtained from all patients individually. This study was approved by the Ethics Committee of Soochow University (approval date: February 28, 2019; No approval number was provided). We followed all relevant guidelines and regulations during the study.

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Conflict of Interest

The authors declare no conflict of interest.

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