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Article

A Predictive Model for Recurrence of Atrial Fibrillation Based on P-Wave Duration in Patients with Early Persistent Atrial Fibrillation Who Underwent Radiofrequency Catheter Ablation

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Abstract

Purpose: To construct a predictive model for the recurrence of atrial fibrillation (AF) based on P-wave duration (PWD) in patients with early persistent AF (PeAF) who underwent radiofrequency catheter ablation (RFCA), with the aim of helping clinicians accurately adjust clinical strategies. **Methods**: Data from patients with early PeAF, who were admitted to the Department of Cardiology at the authors' hospital were collected. Based on predefined inclusion and exclusion criteria, only those who successfully underwent RFCA for the first time were included in the analysis. Pre- and postoperative clinical, echocardiographic, and electrocardiographic data were collected and recorded. Multivariate logistic regression was used to construct a predictive model for AF recurrence based on PWD. The predictive efficacy of each continuous variable and the predictive model were compared using the area under the receiver operating characteristic (ROC) curve. The corresponding nomogram for the predictive model was constructed. Interaction tests were performed to evaluate the predictive efficacy of the model for AF recurrence. **Results**: A total of 237 patients were enrolled and divided into two groups: recurrence (n = 59); and sinus rhythm (n = 178). PWD was greater and left atrial appendage emptying velocity (LAAV) was lower in the recurrence group; these differences were statistically significant ($p < 0.001$). The ROC curve for univariate prediction of AF recurrence revealed that the area under the ROC curve (AUC) for PWD and LAAV were 0.7912 and 0.7713, respectively, which were greater than those of other continuous variables. Compared with PWD alone, the multivariate predictive model containing PWD, left ventricular ejection fraction, and LAAV demonstrated no statistically significant difference in AUC ($p = 0.0553$) but improved the prediction efficiency of correctly reclassifying recurrence rates, net reclassification improvement 14.13% (95% confidence interval: 0.19–28.07%; $p = 0.0469$). The interaction effect did not significantly alter the effectiveness of the predictive models. **Conclusions**: The multivariate model based on PWD measured after RFCA demonstrated better predictive efficacy than the univariate model in patients with early PeAF. These results may contribute to evidence supporting the formulation of personalised treatments for patients with AF.

Keywords

atrial fibrillation; P-wave duration; radiofrequency catheter ablation; predictive model; echocardiography

Introduction

Atrial fibrillation (AF) is one of the most common cardiac arrhythmias and has an increasing negative impact on public health [1]. In 2017, the number of patients with AF was 37.6 million worldwide, which is projected to increase by >60% by 2050 [2]. By then, approximately 5.2 million men and 3.1 million women >60 years of age in China will experience AF [3]. AF can cause a variety of symptoms, such as heart palpitation(s), dizziness, shortness of breath, and fatigue and may also increase the incidence rate and mortality of critical complications including stroke, heart failure, cognitive impairment, and cardiac arrest [4]. AF seriously affects patient quality of life and increases medical costs [5]. Persistent AF (PeAF) is more likely to progress to a more permanent condition than paroxysmal AF (PAF) [6]. AF progression can be slowed by active rhythm control, and patients in rhythm control groups progress at a slower rate than those in ventricular rate control groups [7]. According to the most recent version of the European Society of Cardiology (ESC) guidelines [1], radiofrequency catheter ablation (RFCA) is recommended as the first-line rhythm control strategy for those with PeAF. Despite significant advances in the development of ablation strategies in recent years, the recurrence rate after ablation remains at 8%–40% [8]. The ESC guidelines consider recurrence factors to be an important reference for RFCA and emphasise the importance of evaluating and comprehensively managing risk factors for AF.

In a typical AF remodelling process, the reactive deposition of collagen fibres in the cardiac interstitium causes massive fibrosis [9], followed by changes in normal conduction. Normal sinus stimulation depolarises the atria and produces normal P waves on 12-lead electrocardiography (ECG). P-wave duration (PWD) is associated with atrial depolarisation time, which can be prolonged by intra-atrial and interatrial conduction [10]. In patients with PAF, PWD prolongation is related to AF recurrence after successful pulmonary vein isolation (PVI), and may be associated with left atrial (LA) substrate remodeling [11]. After electrical cardioversion, patients with PeAF exhibit a longer PWD than those with PAF [12]. PeAF with a duration <3 months is known as early PeAF [8]. These individuals comprise the main group of patients with PeAF who undergo rhythm control treatment and may benefit more than those with long-course PeAF [13]. Previously, we found that, in patients with early PeAF, the risk for recurrence after RFCA was independently associated with PWD [14]. Based on previous studies, the present investigation aimed to build a predictive model of AF recurrence based on PWD and to provide evidence supporting accurate clinical treatment and comprehensive management decisions for individuals with early PeAF.

Objects and Methods

Study Population and Inclusion/Exclusion Criteria

This single-centre, retrospective cohort study analysed patients with early PeAF who successfully underwent their first RFCA at the authors' hospital. The study complied with the principles of the Declaration of Helsinki and informed written consent was obtained from all participants. This study was approved by the local Scientific Ethics Committee.

The diagnostic criteria for early PeAF were AF documented by ECG or Holter monitoring and lasting >7 days but <3 months [8]. Exclusion criteria included the following: age <18 years or >80 years; (patients with) thrombus or severe spontaneous echo contrast in the left atrium or LA appendage (LAA); poor quality two-dimensional (2D) images that could not be further analysed and/or processed; ischaemic heart disease, moderate to severe rheumatic valve disease, obstructive hypertrophic cardiomyopathy, and congenital heart disease; previous ablation or surgical therapy for AF; patients in whom the procedure failed; and missing or incomplete clinical data.

Patient clinical data, including general information, medical history, laboratory investigations, and comorbidities were collected from the medical record system. Accordingly, body surface area (BSA) and CHA_2DS_2-VASc score for each patient were calculated.

Acquisition of Echocardiographic Parameters

Before the procedure, an EPIQ 7C device (Philips Healthcare Royal Philips Electronics, Amsterdam, Netherlands) was used to perform transthoracic and transesophageal echocardiography, through which cardiac dimensions and function were assessed and to rule out LA thrombus. Left ventricular ejection fraction (LVEF) was calculated using the biplane Simpson's method, with the mean value of three measurements used for analysis. The "Full Volume" mode was started and the LA endocardium was fully placed in the sampling frame when the corresponding 2D image was clear. All dynamic images were stored in Digital Imaging and Communications in Medicine (i.e., "DICOM") format for further analysis.

Three-dimensional images of the left atrium were analysed using QLAB version 10.5 (Philips Healthcare Royal Philips Electronics, Amsterdam, Netherlands). The 3DQ-A mode was started when the apical four-chamber end-systolic and end-diastolic images were selected. Accordingly, the maximum LA volume (LAVmax) and the minimum LA volume (LAVmin) were calculated. The LA storage function was calculated using the following equation [15]:

Expansion Index (EI) = ([LAVmax - LAVmin]/LAVmin) × 100%

and Diastolic Emptying Index (DEI) = ([LAVmax - LAVmin]/LAVmax) × 100%

LA volume index (LAVI) was calculated using the equation: LAVI = LAV/BSA. Two attending physicians analysed the images separately and were blinded to participant information. The average values for the two physicians were recorded as the final data.

Acquisition of ECG Parameters

All participants underwent ECG within 72 h of RFCA. A Foton FX7402 ECG instrument was used to collect surface 12-lead ECG data. Paper speed and standard sensitivity were set to 25 mm/s and 10 mV, respectively. PWD was defined as the time between the initial line where the P-wave first appeared and the P-wave offset or endpoint. After the images were amplified 10 times at 300 DPI, two independent ECG specialists manually measured the PWD on the workstation. The accuracy of the PWD was set to 1 ms. Three consecutive beats of every lead were measured and averaged, and the maximum PWD was considered in the analysis. ECG images from 20 patients were randomly selected. The images were measured by one observer at three different times to evaluate inter-observer correlation. The same set of ECG images was simultaneously measured by two observers at the same time to evaluate intra-observer correlation.

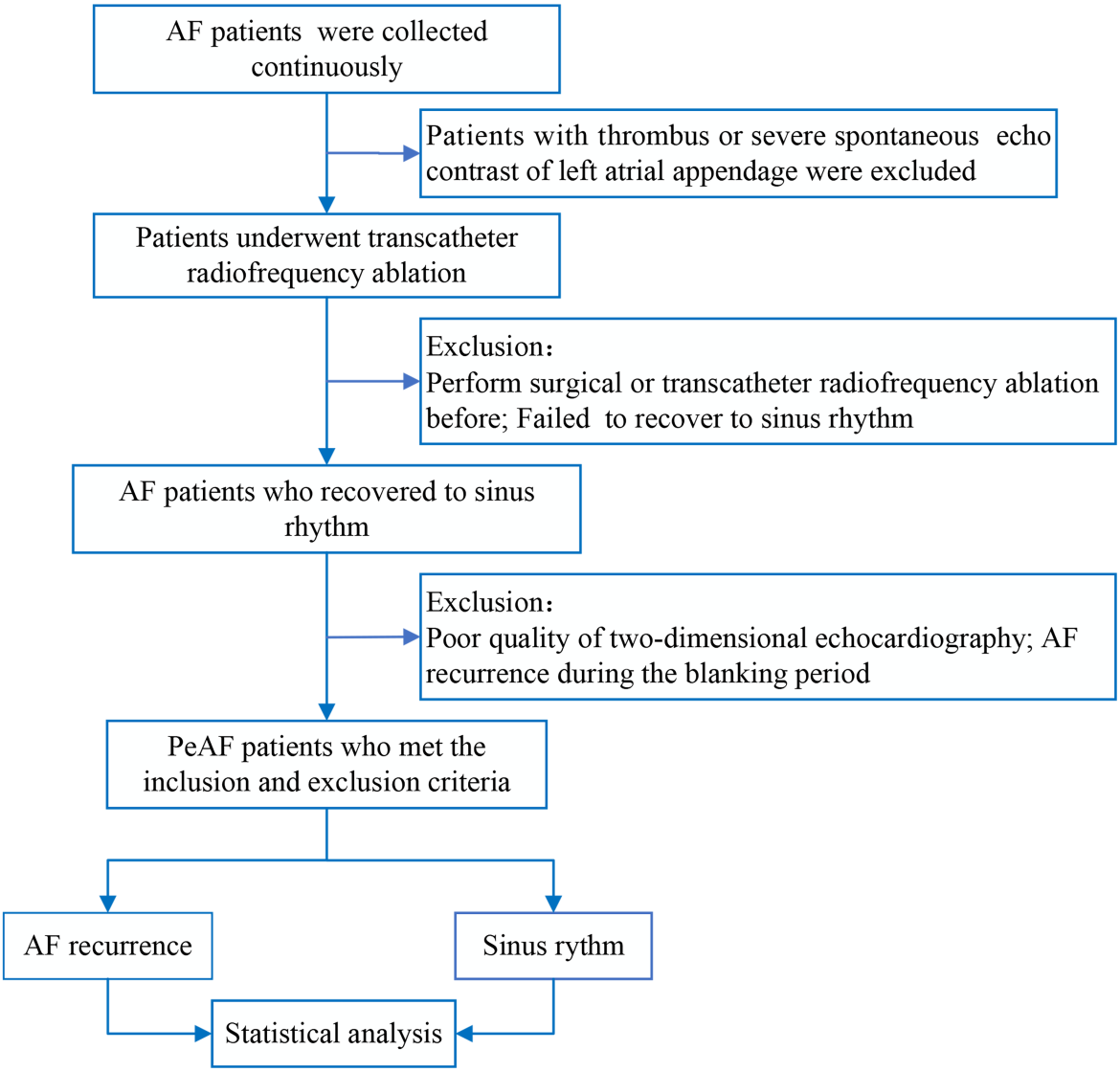

Fig. 1. Flowchart of the study. AF, atrial fibrillation; PeAF, persistent atrial fibrillation.

RFCA Protocol

Patients were connected to the CARTO 3.0 Mapping System (BioSense Webster, Johnson & Johnson, New Brunswick, NJ, USA) before their operation. Coronary sinus electrodes were inserted through the subclavian or femoral veins. After atrial septal puncture, ablation and stimulation catheters were inserted into the left atrium via the femoral vein. All patients underwent three-dimensional reconstruction of the left atrium-pulmonary vein followed by PVI. Treatment decisions for the ablation approach were made at the discretion of the treating physician. In addition to PVI, some patients underwent linear ablation, ablation of complex fractionated electrograms (CFAEs), and substrate modifications. The endpoint of the procedure was a bidirectional conduction block between the left atrium and pulmonary vein, which was confirmed by electrophysiological stimulation.

Postoperative Follow-up

All patients completed their six-month follow-up. Three months after surgery, there was a blanking period that was not included in the recurrence analysis. The patients underwent ECGs every week or when they developed arrhythmia symptoms. Telephone calls and faxes were used to obtain ECG data. Each month, the participants visited the outpatient department for further consultation and 24 h Holter monitoring. All patients were followed up by personnel who were blinded to the treatment plans. AF recurrence was defined as any atrial arrhythmias (AF, atrial tachycardia, or atrial flutter) lasting >30 s documented on ECG [8].

Statistical Analysis

All statistical analyses were performed using R version 3.4.3 (http://www.R-project.org). Continuous variables are expressed as mean ± standard deviation (SD) for

Table 1. Comparison of the echocardiographic and ECG indicators and clinical parameters with different outcome after RFCA.

	Sinus rhythm	Recurrence	*p*-value
n	178	59	
Age	62.98 ± 9.456	62.80 ± 9.22	0.898
Man	146 (82.02%)	49 (83.05%)	0.858
BMI	23.54 ± 2.99	23.92 ± 3.48	0.419
AF duration (months)	9.50 (7.00, 12.00)	9.00 (6.00, 13.00)	0.083
SCR	62.90 (54.40, 72.25)	66.20 (55.85, 70.45)	0.076
BNP	357.20 (216.30, 527.70)	357.5 (246.85, 569.95)	0.131
CHA_2DS_2-VAS_C	2.00 (1.00–3.00)	1.00 (1.00–2.00)	0.226
HR	77.46 ± 15.71	78.29 ± 16.71	0.729
LVEF	54.03 ± 4.98	53.35 ± 5.33	0.371
PWD	115.92 ± 12.88	129.41 ± 10.14	<0.001
LAVImax	40.80 ± 5.14	40.34 ± 4.70	0.550
LAVImin	25.89 ± 3.88	25.67 ± 3.70	0.707
EI	0.59 ± 0.19	0.59 ± 0.20	0.910
DEI	0.36 ± 0.07	0.36 ± 0.08	0.858
LAAV	40.25 (33.53, 48.95)	26.90 (23.90, 44.70)	0.819
Smoke	52 (29.21%)	17 (28.81%)	0.953
Alcohol	34 (19.10%)	16 (27.12%)	0.191
Heart Function			0.982
1	40 (22.73%)	14 (23.73%)	
2	58 (32.96%)	20 (33.90%)	
3	60 (34.09%)	20 (33.90%)	
4	18 (10.23%)	5 (8.49%)	
Antiarrhythmic drugs			0.795
Amiodarone	30 (16.85%)	11 (18.64%)	
Propafenone	22 (12.36%)	9 (15.25%)	
Sotalol	16 (8.99%)	7 (11.86%)	
β-blockers	65 (36.52%)	18 (30.51%)	
Ablation methods			0.984
PVI + LA roof lesion	47 (26.40%)	18 (30.51%)	
PVI + mitral isthmus	31 (17.42%)	10 (16.95%)	
PVI + CTI	37 (20.79%)	15 (25.42%)	
PVI + CFAEs	20 (11.24%)	7 (11.86%)	
PVI + substrate modification	28 (15.73%)	9 (15.25%)	
DM	39 (21.91%)	10 (16.95%)	0.415
Hypertension	46 (25.84%)	15 (25.42%)	0.949
CHF	27 (15.17%)	13 (22.03%)	0.222
Hyperlipidemia	25 (14.05%)	12 (20.34%)	0.248
Stroke or TIA	28 (15.73%)	9 (15.25%)	0.930
Vascular Disease	18 (10.11%)	4 (6.78%)	0.445

The results are expressed as mean ± (SD)/Median (Q1, Q3)/n (%). RFCA, radiofrequency catheter ablation; BMI, body mass index; AF, atrial fibrillation; SCR, serum creatinine concentration; BNP, B-type natriuretic peptide; HR, heart rate; LVEF, left ventricular ejection fraction; PWD, P wave duration; LAVImax, maximum left atrial volume index; LAVImin, minimum left atrial volume index; EI, expansion index; DEI, diastolic emptying index; LAAV, left atrial appendage emptying velocity; PVI, pulmonary vein isolation; LA, left atrial; CTI, cavotricuspid isthmus; CFAEs, complex fractionated electrograms; DM, diabetes mellitus; CHF, congestive heart failure; TIA, transient ischemia attack.

data that were normally distributed or as median and interquartile range (IQR) for data with a skewed distribution. Continuous variables were compared using the Student's *t*-test, or Mann–Whitney U test, as appropriate. Categorical variables are expressed as frequencies or rates (%). The chi-squared test was used for comparisons between groups. Pearson's correlation analysis was used to evaluate intra- and inter-observer correlations.

The predictive accuracy of each continuous variable was quantified using the area under the receiver operat-

Table 2. Univariate and multivariate logistic regression analysis.

	Univariate logistic regression			Multivariate logistic regression	
	Statistics	RE	*p*-value	OR	*p*-value
Age	62.93 ± 9.38	1.00 (0.97–1.03)	0.897		
Female (%)	42 (17.72%)	0.93 (0.43–2.03)	0.858		
BMI	23.64 ± 3.12	1.04 (0.95–1.14)	0.418		
AF duration	9.00 (7.00, 12.00)	1.02 (0.95–1.10)	0.558		
SCR	63.90 (54.40, 71.70)	1.00 (0.99–1.02)	0.618		
BNP	357.50 (232.60, 537.90)	1.00 (1.00–1.00)	0.388		
CHA_2DS_2-VAS_C	1.00 (1.00, 2.00)	0.84 (0.66–1.06)	0.144		
HR	77.66 ± 15.93	1.00 (0.99–1.02)	0.727		
LVEF	53.86 ± 5.06	0.97 (0.92–1.03)	0.370	0.95 (0.88–1.02)	0.158
BMI	23.64 ± 3.12	1.04 (0.95–1.14)	0.418		
PWD	119.27 ± 13.56	1.11 (1.07–1.14)	<0.001	1.10 (1.06–1.14)	<0.001
LAVImax	40.68 ± 5.03	0.98 (0.93–1.04)	0.548		
LAVImin	25.84 ± 3.83	0.99 (0.91–1.07)	0.706		
EI	0.59 ± 0.19	0.91 (0.19–4.34)	0.910		
AEI	0.36 ± 0.08	0.70 (0.01–35.16)	0.857		
LAAV	38.50 (30.40, 49.00)	0.91 (0.88–0.95)	<0.001	0.93 (0.90–0.96)	<0.001
Smoke	69 (29.114%)	0.98 (0.51–1.88)	0.953		
Alcohol	50 (21.097%)	1.58 (0.79–3.13)	0.193		
Heart function					
1	54 (22.98%)				
2	78 (33.19%)	0.99 (0.45–2.18)	0.971		
3	80 (34.04%)	0.95 (0.43–2.10)	0.904		
4	23 (9.79%)	0.79 (0.25–2.54)	0.697		
Antiarrhythmic drugs					
Amiodarone	41 (17.30%)	1.13 (0.53–2.43)	0.753		
Propafenone	31 (13.08%)	1.28 (0.55–2.95)	0.568		
Sotalol	23 (9.70%)	1.36 (0.53–3.50)	0.519		
β-blockers	83 (35.02%)	1.03 (0.56–1.90)	0.915		
Ablation methods					
PVI + LA roof lesion	65 (19.88%)	1.22 (0.64–2.34)	0.541		
PVI + mitral isthmus	41 (12.54)	0.97 (0.44–2.12)	0.935		
PVI + CTI	52 (21.94%)	1.30 (0.65–2.59)	0.456		
PVI + CFAEs	27 (11.39%)	1.06 (0.43–2.66)	0.895		
PVI + substrate modification	37 (15.61%)	0.96 (0.43–2.18)	0.930		
DM	49 (20.68%)	0.73 (0.34–1.57)	0.416		
Hypertension	61 (25.74%)	0.98 (0.50–1.92)	0.949		
CHF	40 (16.88%)	1.58 (0.76–3.31)	0.225		
Hyperlipidemia	37 (15.62%)	1.56 (0.73–3.35)	0.251		
Stroke or TIA	37 (15.62%)	0.96 (0.43–2.18)	0.930		
Vascular Disease	22 (9.28%)	0.65 (0.21–1.99)	0.448		

The results are expressed as mean ± (SD)/Median (Q1, Q3)/n (%). RFCA, radiofrequency catheter ablation; BMI, body mass index; AF, atrial fibrillation; SCR, serum creatinine concentration; BNP, B-type natriuretic peptide; HR, heart rate; LVEF, left ventricular ejection fraction; PWD, P wave duration; LAVImax, maximum left atrial volume index; LAVImin, minimum left atrial volume index; EI, expansion index; DEI, diastolic emptying index; LAAV, left atrial appendage emptying velocity; PVI, pulmonary vein isolation; LA, left atrial; CTI, cavotricuspid isthmus; CFAEs, complex fractionated electrograms; DM, diabetes mellitus; CHF, congestive heart failure; TIA, transient ischemia attack.

ing characteristic (ROC) curve (AUC) [16]. Univariate and multivariate logistic models were used to assess the association between variables and AF recurrence. All variables with $p < 0.1$ in univariate analysis were included in the multivariate analysis. The likelihood ratio test with stepwise backward selection was applied to multivariate logistic regression. A bootstrap method was used to determine the best subset of factors to avoid overfitting the data for the development sample. Compared with the univariate model, it was calculated whether the AUC, net reclassification im-

Table 3. ROC of each continuous variable to predict the AF recurrence.

Test	AUC	95% CI	Best threshold	Specificity	Sensitivity
PWD	0.7912	0.7262–0.8562	127.5000	0.8371	0.6102
LAAV	0.7713	0.6766–0.8661	28.7500	0.9944	0.6949
LAVImax	0.5239	0.4399–0.6079	39.4333	0.6011	0.4915
LAVImin	0.5161	0.4324–0.5998	26.7667	0.3764	0.6949
PI	0.5068	0.4190–0.5946	0.5415	0.5674	0.5085
AEI	0.5068	0.4190–0.5946	0.3513	0.5674	0.5085
CHA_2DS_2-VAS_C	0.5582	0.4763–0.6401	1.5000	0.5112	0.5763

ROC, receiver operating characteristic curve; AUC, area under curve; CI, confidence interval; PWD, P wave duration; LAAV, left atrial appendage emptying velocity; LAVImax, maximum left atrial volume index; LAVImin, minimum left atrial volume index; EI, expansion index; DEI, diastolic emptying index.

provement (NRI), and integrated discrimination improvement (IDI) of the multivariate model were improved. The model with the best predictive efficiency was selected, and the corresponding nomogram was constructed. Stratification analysis and interaction tests were performed to assess whether factors affected the prediction of AF recurrence using the model. Differences with $p < 0.05$ were considered to be statistically significant.

Results

Flowchart Illustrating Patient Selection and Clinical Data of the Participants

From August 2016 to February 2021, 270 patients were screened, 33 of whom were excluded based on the exclusion criteria, as follows (Fig. 1): thrombus or severe spontaneous echo contrast of the LAA (n =12); underwent radiofrequency ablation by either surgery or catheter before surgery (n = 9); failed RFCA (n = 4); poor 2D echocardiography images (n = 5); and relapse within three months after the operation (n = 3). As such, the final population for analysis included 237 individuals (195 male, 42 female), all of whom underwent PVI. In a subset of patients, $\geq$1 additional techniques were performed, including LA roof lesion (n = 65), mitral isthmus line (n = 41), cavotricuspid isthmus (CTI) ablation (n = 52), and CFAEs ablation (n = 27). Additive substrate modification was performed in addition to PVI in 37 patients. These data were subjected to further statistical analyses.

Comparison of Baseline Data between the Recurrence and Sinus Rhythm Groups

The enrolled patients were divided into a recurrence group (n = 59) and a sinus rhythm group (n = 178) according to their 3–6 months recurrence status after RFCA. The baseline characteristics of the two groups are summarised in Table 1. PWD was greater and LAA emptying velocity (LAAV) was lower in the recurrence group. These differences were statistically significant ($p < 0.001$). Differences in other indicators were not statistically significant.

Univariate and Multivariate Logistic Regression Analysis

We used the AF recurrence after the operation as the dependent variable (recurrence: Y = 1) and echocardiographic and ECG indicators and clinical parameters, including PWD, as the independent variables to perform univariate and multivariate logistic regression analysis. The results showed that PWD and LAAV were independent risk factors for AF recurrence ($p < 0.001$). Table 2 shows the detailed data.

Test of Reproducibility

The interobserver correlation coefficient was 0.970 (95% confidence interval (CI): 0.8756–0.9932; $p < 0.001$). The intraobserver correlation coefficient was 0.933 (95% CI: 0.7337–0.9843; $p < 0.001$).

ROC Curve for Each Continuous Variable to Predict AF Recurrence

The AUC, sensitivity, and specificity for each ROC curve for predicting AF recurrence in patients with early PeAF are summarised in Table 3. The AUC for PWD and LAAV were 0.7912 and 0.7713, respectively, which were greater than those of other continuous variables. The thresholds for PWD and LAAV for predicting recurrence were 127.5 ms and 28.7 cm/s.

Construction of a Predictive Model Based on PWD and Corresponding Nomogram

PWD, LVEF, and LAAV were independent predictors of AF recurrence, and identified using multivariate adjusted logistic regression analysis. Therefore, a stepwise (stepAIC) selected model was constructed:

Logit (P) = –7.29568 + 0.09449 × PWD – 0.05181 × LVEF – 0.07246 × LAAV

The AUC for this model was greater than that for PWD alone (0.839 > 0.791, $p = 0.055$). The continuous NRI

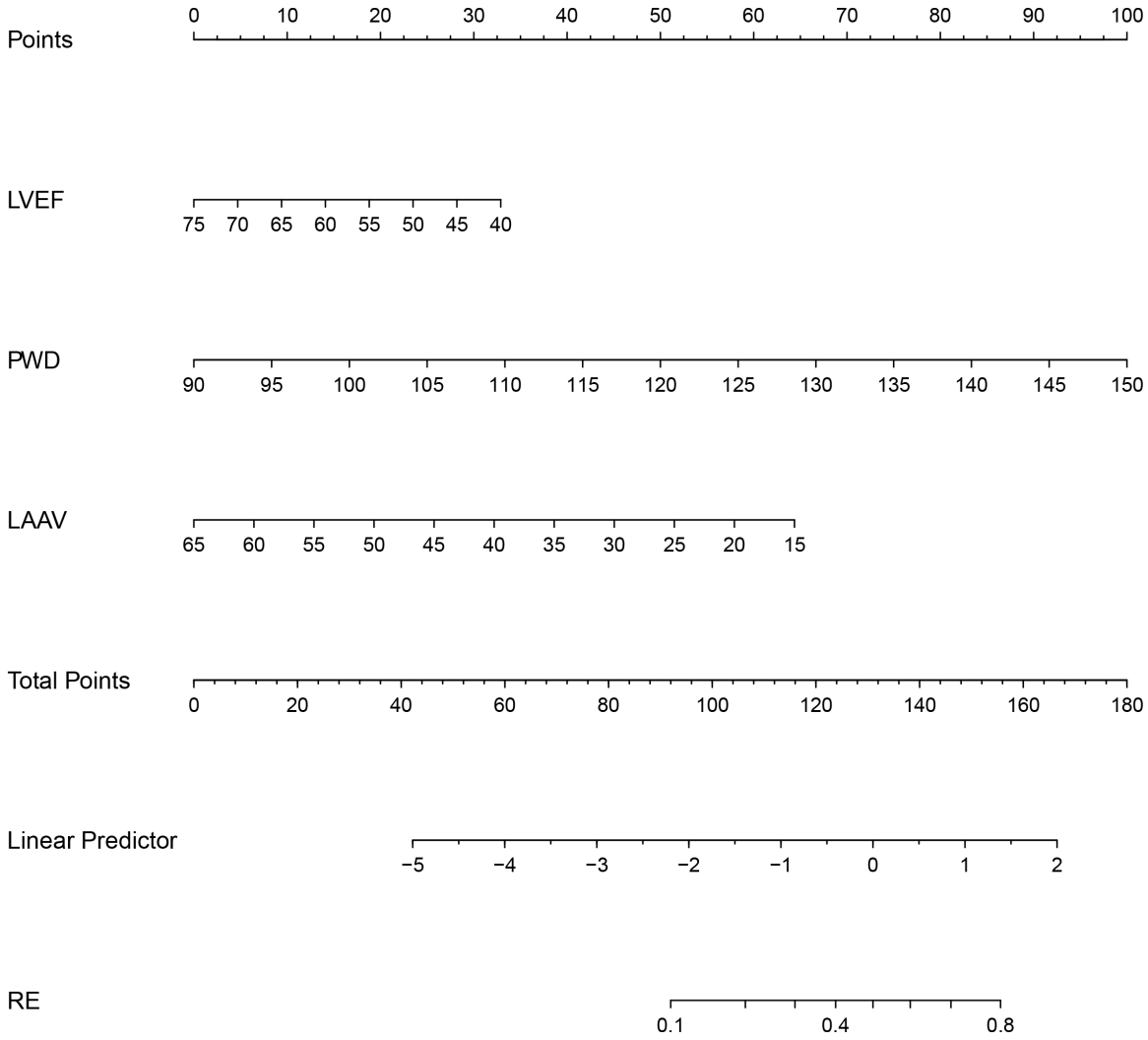

Fig. 2. Echocardiographic nomogram for the prediction of atrial fibrillation recurrence. LVEF, left ventricular ejection fraction; PWD, P-wave duration; LAAV, left atrial appendage emptying velocity; RE, recurrence of atrial fibrillation.

was then calculated for a model including LAAV and LVEF on top of the previously established univariate model for AF recurrence. A model containing LAAV and LVEF, in addition to PWD, had a continuous NRI of 14.13% (95% CI: 0.19–28.07%; $p = 0.0469$), driven by a correct reclassification of recurrence in 15.15% ($p = 0.0228$) and sinus rhythm in –1.12% ($p = 0.6371$) (**Supplementary Table 1**). The nomogram for the PWD-based predictive model is presented in Fig. 2.

Stratification Analysis and Interaction Tests

Results of analysis revealed that sex, alcohol consumption, smoking, hypertension, diabetes, peripheral vascular disease, history of stroke or transient ischaemic attack (TIA), hyperlipidaemia, and heart function did not significantly alter the effectiveness of the predictive model (Fig. 3).

Discussion

The present study aimed to develop a predictive model for AF recurrence based on PWD in patients with early persistent AF who underwent RFCA, and yielded four main findings. First, comparisons of baseline data between the recurrence and sinus rhythm groups revealed that differences in PWD and LAAV were statistically significant. Second, the ROC curve for each continuous variable used to predict AF recurrence demonstrated that the AUC for PWD was the greatest. Third, a PWD-based model constructed using multivariate logistic regression demonstrated higher predictive efficiency than univariate models. Additionally, we constructed a corresponding nomogram of the model to provide clinicians with a convenient visual tool. Finally, the stratification analysis and interaction tests excluded the effects of confounding factors on the predictive efficiency of the model.

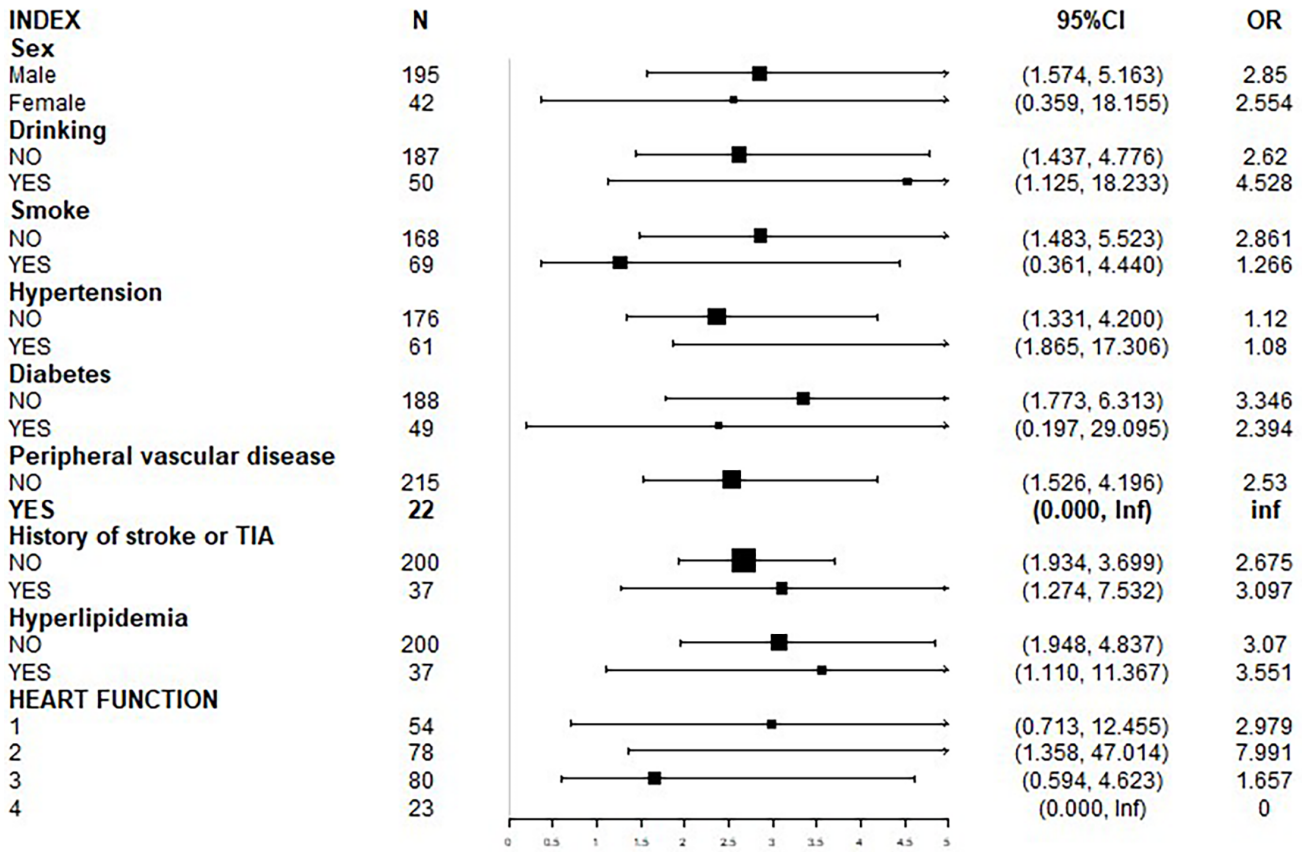

Fig. 3. Stratification analysis and interaction tests. Adjusted for the follows: gender, drinking, smoke, hypertension, diabetes, peripheral artery disease, history of stroke or TIA, hyperlipidemia, heart function. TIA, transient ischemia attack.

Several studies have constructed predictive models for patients with PAF after transcatheter RFCA; however, relatively few have addressed early PeAF. Based on the univariate prediction of AF recurrence, a multivariate predictive model was established in our study, including PWD, LAAV, and LVEF, for which data can be easily obtained in clinical settings. To provide clinicians with an easy-to-use tool, we constructed a nomogram based on multivariate logistic regression. The model formula can be better visualised and applied to clinical decisions using a nomogram [17]. In practice, clinicians use scores corresponding to PWD, LAAV, and LVEF in the nomogram and draw a straight line to the total score to obtain the corresponding recurrence probability. For example, we selected a 67-year-old male patient whose LVEF, PWD and LAAV were 55%, 125 ms and 40 m/s, respectively, and the corresponding scores were 19, 58 and 33. Then we obtained a total score of 110. According to the corresponding total score, we can obtain that the probability of atrial fibrillation recurrence after radiofrequency catheter ablation is 0.2, which is a low risk. The PWD-based predictive model helps to identify patients with AF who are at a greater risk for recurrence and may require more extensive treatment.

A previous study reported an association between short- and long-term PWD and an increased risk for AF in a large primary care population [18]. In patients with PAF, the PWD measured using 12-lead ECG is an effective predictor of AF recurrence risk after RFCA [19]. A maximum PWD >140 ms [11] or PWD in lead II >125 ms [20] is related to an increased risk for postoperative AF. The target population of the present study included patients with early PeAF. A PWD of 127.5 ms was used as the threshold for predicting postoperative AF recurrence. In patients with PeAF, a prolonged PWD, measured using signal-averaged ECG, has been reported to be a predictor of AF recurrence after electrical cardioversion [21–23]. In patients with PeAF and refractory PAF, PWD after circumferential antral ablation for pulmonary vein isolation is an independent risk factor for single-procedure success [24].

A prolonged PWD may be related to atrial enlargement and/or slow conduction [25]. A low-voltage structure (LVS) prolongs LA activation time, which is reflected as a prolongation of PWD on digitally amplified ECG [26]. The extent of LA LVS is associated with patient history of AF and progresses from PAF to PeAF and permanent forms of AF [27]. Correspondingly, the PWD of patients with PeAF is longer than that of PAF patients [28]. In patients with PeAF, conduction in the area related to a significant LA LVS is delayed [29]. The determination of the LA LVS is mainly based on the voltage measurement of CARTO mapping. In this study, LA LVS modification was performed to block potential pathways based on CARTO mapping during

RFCA. Typical LA LVS may be related to LA remodelling. Chen *et al*. [30] identified the LA LVS as a scar area and found that prolonged PWD was independently related to LA scarring. However, voltage mapping using CARTO is affected by many factors [31], including the recording electrode size, activation vector, and angle of incidence. PWD measured using surface 12-lead ECG is easy to obtain and can be used as a surrogate for LA remodelling changes related to the AF burden [24].

The construction of a predictive model for AF recurrence based on PWD provides important scientific evidence for risk stratification, treatment strategies, follow-up, and refined management of patients with early PeAF. For patients with AF whose recurrence probability is >0.5, as shown in the nomogram, more attention should be devoted to the treatment of atrial pathological remodelling, such as adding drugs to reverse myocardial remodelling as a secondary prevention strategy for patients with AF after RFCA.

Limitations

This single-centre retrospective study had some limitations. First, the follow-up period was relatively short. Although the patients in this study received frequent ECG and heart tests, some patients in the sinus rhythm group may have undetected recurrent atrial fibrillation. Second, we did not standardise the ablation approach. Ablation is a risk factor for AF recurrence in patients with AF. Patients were enrolled during August 2016 to February 2021. Many potential influencing factors may change during the five years. We did not comprehensively report all the interventions and changes in the medical plan; therefore, AF may have improved in some patients due to the implementation of effective therapies. Third, the constructed model was not validated in the present study and we acknowledge that model validation is as important as model construction. As such, we aim to validate the model in a future study.

Conclusions

Compared to the univariate model of PWD, a multivariate predictive model including PWD, LVEF, and LAAV, improved the predictive effect of correctly reclassifying recurrence rates. As convenient and rapid clinical examination methods, ECG and echocardiography can provide strong support for the comprehensive management of patients with AF and informing the design of personalised treatment programs.

Availability of Data and Materials

The original data and Materials of our study are available from the corresponding author upon reasonable request.

Author Contributions

HH performed the study and wrote the manuscript; MX and YM contributed to the conception of the study and performed the data analysis; CQ helped perform the analysis with constructive discussions; ZY contributed significantly to analysis and manuscript preparation; LY contributed interpretation of data for the work and provided fund support. All authors reviewed the manuscript. All authors have read and agreed to the published version of the manuscript. All authors contributed to editorial changes in the manuscript. All authors have participated sufficiently in the work to take public responsibility for appropriate portions of the content and agreed to be accountable for all aspects of the work in ensuring that questions related to its accuracy or integrity.

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. The study protocol received approval from the Scientific Ethics Committee of The Third Affiliated Hospital of Soochow University (2016TNo.44). We followed all relevant guidelines and regulations during the study.

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Conflict of Interest

The authors declare no conflict of interest.

Supplementary Material

Supplementary material associated with this article can be found, in the online version, at https://doi.org/10.59958/hsf.6993.

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