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RESEARCH

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A Nomogram utilizing ECG P-wave parameters to predict recurrence risk following catheter ablation in paroxysmal atrial fibrillation

Li-juan Yu[1,2], Xue-Hai Chen[1], Zhe Xu[1], Ke-Zeng Gong[1] and Fei-Long Zhang[1*]

Abstract

Objective The objective of this study is to assess the predictive utility of perioperative P-wave parameters in patients with paroxysmal atrial fibrillation (PAF) undergoing catheter ablation, and to develop a predictive model using these parameters.

Methods A total of 213 patients with PAF undergoing catheter ablation were retrospectively analyzed. P-wave parameters were measured within 3 days preoperatively and on the day postoperatively to determine their predictive significance for postoperative PAF recurrence.

Results Post-ablation, PAF did not recur in 168 patients, while 45 experienced recurrence. Significant differences were observed in preoperative P-wave parameters as Maximum P Wave Duration(Pmax), absolute value of P Wave Terminal Force of V1 (PtfV1) and P Wave Dispersion(Pd), postoperative P-wave parameters as P Wave Duration ($PWD_{II, III, aVF}$), Pmax, P Wave Area(P-area), absolute value of PtfV1 and Pd, and changes in perioperative P-wave parameters (Delta-Pmax, Delta-PtfV1 absolute value, Delta-Pd, Delta-$PWD_{II, III, aVF}$). Univariate logistic regression, receiver operating characteristic (ROC) curve analysis, and hazard ratio assessment identified predictive indicators for postoperative recurrence, including Pmax, PtfV1 absolute value, Pd, post-P area, post-$PWD_{II, III, aVF}$ and Delta-$pwd_{II, III, aVF}$). A personalized nomogram model based on these P-wave parameters was developed. Calibration curve assessment demonstrated that the predictive performance of the nomogram for PAF recurrence following catheter ablation closely matched actual observed outcomes. ROC curve analysis indicated a sensitivity of 89.3% for the model, and decision curve analysis confirmed its significantly favorable predictive use and clinical benefits.

Conclusions P-wave parameters like $PWD_{I,I,I}$, PWDaVF, Pmax, Pd, and PtfV1 serve as predictors of PAF recurrence following catheter ablation. The nomogram model constructed using these P-wave parameters demonstrates robust predictive performance.

Highlights

- Abnormal changes in P-wave parameters indicative of atrial electrical remodeling often manifest earlier than changes in other indicators reflecting atrial structural remodeling in paroxysmal atrial fibrillation.

*Correspondence:
Fei-Long Zhang
cardizhang@163.com

Full list of author information is available at the end of the article

- Preoperative absolute values of Maximum P Wave Duration, P Wave Dispersion, and P Wave Terminal Force of V1, as well as postoperative absolute values of Maximum P Wave Duration, P Wave Duration, P Wave Dispersion, P Wave Terminal Force of V1, and P Wave Area, demonstrate strong predictive value for recurrence risk of paroxysmal atrial fibrillation after Catheter Ablation.
- The nomogram model based on P-wave parameters before and after catheter ablation exhibits notably strong predictive performance and offers significant clinical benefits.

Keywords Catheter ablation, Electronic cardiogram, Nomogram model, P-wave parameters, Paroxysmal atrial fibrillation, Recurrent atrial fibrillation

Introduction

Paroxysmal atrial fibrillation (PAF) is prevalent in clinical settings. Current treatment strategies for atrial fibrillation (AF) primarily involve sinus rhythm conversion, ventricular rate control, and anticoagulation therapy to prevent thromboembolism [1]. Catheter ablation has emerged as the preferred therapeutic approach for AF due to its efficacy, safety, and minimally invasive nature. However, despite these advantages, there remains a high recurrence rate of 20–40% following the initial catheter ablation for PAF [2].

The development of AF is significantly influenced by both electrical and structural remodeling of the atrium. As AF progresses, the left atrial electrical remodeling further aggravates, contributing to the transition from PAF to persistent AF. Recent studies have found that many indicators as F-wave frequency, orthogonal P-wave shape, Fibrillation wave amplitude, dominant atrial frequency, Sample entropy, Fibrillation wave amplitude and atrial tissue fibrosis, are associated with the recurrence of paroxysmal atrial fibrillation, but some indicators need invasive examination, and some indicators still lack the best and efficient clinical examination means [3–8]. In addition, intracardiac electrophysiological examinations are used for assessing the extent of atrial electrical remodeling, but their high cost and invasive nature limit widespread patient acceptance. In contrast, 12-lead synchronous surface electrocardiogram (ECG) examinations are simpler and widely used in clinical practice, serving as a key tool for diagnosing and studying heart diseases. P-wave parameters derived from ECG have demonstrated associations with AF recurrence. [9, 10]

In this study, the predictive significance of P-wave parameters and their changes in predicting PAF recurrence in patients following catheter ablation was analyzed. A nomogram predictive model was developed to assist clinicians in identifying patients and selecting optimal treatment strategies, while providing comprehensive management and early warning guidance for patients with AF. This research carries significant clinical implications and potential socio-economic benefits.

Materials and methods

Study participants

In this single-center, retrospective study, 213 patients with PAF were enrolled who underwent their first catheter ablation and received regular follow-up at the Department of Cardiology, Union Hospital Affiliated to Fujian Medical University from January 2017 to December 2020.

Inclusion criteria: (1) Patients meeting the 2020 ESC diagnostic criteria for PAF, experiencing symptomatic atrial fibrillation despite regular antiarrhythmic drug therapy, and consenting to further rhythm control treatment; (2) Patients had undergone initial catheter ablation; (3) Agree to surgical intervention; (4) Aged ≥ 18 years old; (5) Left atrial and/or left atrial appendage thrombosis excluded via preoperative transesophageal echocardiography or left atrial CT angiography; (6) Cardiac function graded as NYHA class I-III; and (7) Agree to undergo regular follow-up post-surgery.

Exclusion criteria: (1) Patients younger than 18 years of age; (2) With a history of previous cardiac surgery; (3) Patients with NYHA class IV cardiac function or left ventricular ejection fraction (LVEF) less than 50%; (4) Patients diagnosed with preexcitation syndrome, congenital heart disease, or cardiomyopathy; (5) Patients with pacemaker implantation affecting ECG rhythm; (6) Patients with severe liver or kidney dysfunction; (7) Patients with hyperthyroidism; and (8) Those unable to cooperate with examinations, lost to follow-up, or had incomplete data.

General information

The preoperative clinical baseline data of the selected patients and preoperative 12-lead surface ECG data in sinus rhythm were retrospectively collected, comprising measurements such as left atrial anteroposterior diameter, left ventricular end-diastolic diameter, left ventricular ejection fraction (LVEF), and E/E' value. Postoperative medication records included details on antiarrhythmic drugs, anticoagulants, antihypertensive agents, and lipid-lowering drugs.

P wave parameters of surface ECG

The 12-lead conventional ECG was conducted within 3 days preoperatively and on the day after catheter ablation, during periods of sinus rhythm. For each ECG, the stable baseline cardiac cycle was selected to measure related P-wave indices across all 12 leads, including P Wave Duration(PWD), P Wave Amplitude(PWA), P Wave Terminal Force(Ptf), and Inter Atrial Block(IAB). Based on measurements of PWD and PWA, parameters like P Wave Index(P-index), P Wave Area(P-area), Maximum P Wave Duration(Pmax), and P Wave Dispersion(Pd) were computed. Three to five consecutive P waves were collected during each assessment, and the average value was calculated. The entire measurement process of P-wave parameters was conducted by the same physician throughout the study to ensure consistency. The definition, normal range values, measurement and calculation methods of P-wave parameters was detailed in Supplemental information.

Catheter ablation surgical scheme

Radiofrequency ablation was performed by the same surgical team in accordance with standard operating procedures described in detail in the Supplemental information.

Postoperative follow-up

All patients underwent routine ECG monitoring for 24 h postoperatively, with a 12-lead ECG in sinus rhythm recorded immediately after the procedure. Anticoagulant therapy was administered for at least 3 months following surgery. After this period, the CHA2DS2-VASc score was used to determine the necessity of continuing anticoagulant therapy. Antiarrhythmic drugs were not routinely prescribed, and were only used if arrhythmias necessitated their use. All antiarrhythmic drugs were discontinued after 3 months. Follow-up was conducted monthly. Routine ECG examinations were performed once a month, with opportunistic routine ECG and dynamic ECG examinations carried out when patients experienced discomfort symptoms. Regular outpatient follow-ups included routine ECG, 72-hour dynamic ECG, and echocardiography, conducted at 1 month, and then at 3, 6, 9, and 12 months postoperatively.

Statistical analysis

All data in this study were processed using R version 4.2.0 software. Categorical variables of count data are expressed as frequency (%), while continuous variables with a normal distribution are expressed as mean ± standard deviation. Non-normally distributed continuous variables are expressed as median values, and normality tests and variance homogeneity tests were performed. The independent sample t-test was used to compare data between the two groups, with $P < 0.05$ considered statistically significant. Significant ECG index variables identified from the t-test underwent further analysis through receiver operating characteristic (ROC) curve analysis using the pROC software. The optimal cutoff value for P-wave parameters on surface ECG was determined by assessing whether the threshold parameter equaled the "best" value. Single-factor logistic regression analysis was used to assess the relationship between P-wave parameters and AF recurrence after catheter ablation. Hazard ratio analysis was performed using the Forestplot package, and a nomogram for predicting the recurrence risk of PAF after catheter ablation, dominated by ECG P-wave parameters, was constructed using the rms software package. Consistency between predicted risks and observed outcomes was assessed using a calibration curve, while internal validation of the model was conducted through the Hosmer-Lemeshow test and Bootstrap method, resampling 1000 times. Finally, clinical decision curve analysis (DCA) was carried out using the ggDCA software package to verify the clinical prediction performance and benefits of the nomogram model.

Results

Basic clinical data

No significant differences were observed between the two groups in terms of gender, age, smoking status, alcohol consumption, BMI, duration of AF, underlying diseases, CHA2DS2-VASc score, HAS-BLED score, preoperative serum biochemical indexes, echocardiographic indexes, or the postoperative use of antiarrhythmic drugs and anticoagulants (Table 1).

Analysis of ECG P-wave parameters before ablation

The preoperative P-wave parameters (indicates as pre-) of all patients were analyzed and compared (Table 2). Significant differences were observed between the non-recurrence group and the recurrence group in pre-Pmax (124.21 ± 12.03 vs. 128.84 ± 12.68, $P = 0.024$), pre-Pd (45.58 ± 13.16 vs. 51.29 ± 15.09, $P = 0.013$), and pre-PtfV1 absolute value (0.03 ± 0.02 vs. 0.04 ± 0.02, $P = 0.028$). Other preoperative ECG indexes did not indicate significant differences ($P > 0.05$). Although the PWD of the non-recurrence group was larger than that of the recurrence group, this difference was not statistically significant (sTable S1, sFigure S1). Similarly, no significant difference was discovered in the PWA between the non-recurrence group and the recurrence group (sTable S2, sFigure S2).

Analysis of P-wave parameters after ablation

The postoperative P-wave parameters (indicates as post-) were analyzed (Table 3), revealing significant differences between the non-recurrence group and the recurrence group in several indexes: post-PWDII ($P < 0.001$), post-PWDIII ($P < 0.001$), post-PWDaVF ($P = 0.001$), post-Pmax ($P < 0.001$), post-P-area ($P = 0.022$), post-PtfV1 absolute value ($P < 0.001$), post-pIAB ($P = 0.001$), post-Pd

Table 1 Comparison of basic clinical data

Variables	No-recurrence group (*N* = 168)	Recurrence group (*N* = 45)	*P*-value
Sex			
Male N (%)	71(42.3%)	26(57.8%)	0.091
Age (years)	61.5(54∽67)	62(56∽68)	0.357
Duration of AF (months)	24(6∽48)	24(12∽60)	0.223
BMI(Kg/m^2)	22.79 ± 6.81	22.75 ± 5.58	0.970
Smoking N (%)	42(25%)	6(13.3%)	0.144
Alcohol consumption N (%)	53(31.5%)	8(17.8%)	0.103
Combined underlying disease			
Hypertension N (%)	72(42.9%)	27(60.0%)	0.060
Diabetes N (%)	20(11.9%)	7(15.6%)	0.688
Coronary heart disease N (%)	30(17.9%)	8(17.8%)	0.977
Heart failure N (%)	1(0.6%)	0(0%)	0.608
Stroke /TIA N (%)	0(0%)	2(4.4%)	0.061
Hyperlipidemia N (%)	62(36.9%)	16(35.6%)	0.627
Pulmonary hypertension N (%)	12(7.1%)	6(13.3%)	0.306
Combined arrhythmia			
Atrial flutter N (%)	20(11.9%)	6(13.3%)	0.997
Atrial tachycardia N (%)	36(21.4%)	8(17.8%)	0.741
CHA2DS2-vasc score (points)			0.428
0	39(23.2%)	7(15.6%)	
1	51(30.4%)	12(26.7%)	
2	40(23.8%)	13(28.9%)	
3	23(13.7%)	6(13.3%)	
4	9(5.4%)	6(13.3%)	
5	6(3.6%)	1(2.2%)	
HAS-BLED score (points)			0.159
0	77(45.8%)	18(40.0%)	
1	64(38.1%)	14(31.1%)	
2	25(14.9%)	13(28.9%)	
3	2(1.2%)	0(0%)	
Serum biochemical index			
NT-probnp (pg/ml)	194.2 ± 583.83	129.84 ± 187.46	0.467
D-dimer (ng/ml)	0.43 ± 1.54	0.30 ± 0.15	0.592
TC (mmol/ml)	4.45 ± 0.92	4.43 ± 1.04	0.915
TG (mmol/ml)	1.45 ± 0.70	1.60 ± 1.15	0.281
Echocardiography			
LAD (mm)	31.78 ± 11.09	33.04 ± 10.47	0.494
LVEDD (mm)	43.32 ± 13.76	45.51 ± 10.61	0.323
Lvef (%)	61.99 ± 20.08	68.35 ± 11.67	0.053
E/E 'value	10.19 ± 4.60	10.69 ± 4.94	0.525
Antiarrhythmic drug therapy			
Amiodarone N (%)	20(11.9%)	3(6.7%)	0.462
Propafenone N (%)	70(41.7%)	20(44.4%)	0.869
Beta blocker N (%)	31(18.5%)	12(26.7%)	0.312
Anticoagulant medication			
Rivaroxaban N (%)	120(71.4%)	26(57.8%)	0.116
Dabigatran N (%)	26(15.5%)	11(24.4%)	0.235
Warfarin N (%)	21(12.5%)	8(17.8%)	0.502
Acei/arb (n)	31(18.5%)	12(26.7%)	0.312
Statins N	44(26.2%)	14(31.1%)	0.638

* $P < 0.05$

Table 2 P wave parameters of 12-lead electrocardiogram before ablation

P wave parameters	No-recurrence group (*N* = 168)	Recurrence group (*N* = 45)	*P* value
pre-HR(Times/min)	69.18 ± 12.32	69.27 ± 9.81	0.967
pre-QRS interval(ms)	82.39 ± 14.25	83.22 ± 21.70	0.759
pre-QTc interval(ms)	415.44 ± 25.89	409.73 ± 31.92	0.214
pre-PR interval(ms)	148.90 ± 21.21	151.02 ± 23.96	0.562
pre-PWD_I(ms)	103.01 ± 17.90	105.11 ± 18.50	0.489
pre-PWD_{II}(ms)	114.03 ± 14.18	118.11 ± 15.82	0.096
pre-PWD_{III}(ms)	102.54 ± 17.88	104.16 ± 17.04	0.586
pre-PWD_{aVR}(ms)	106.34 ± 15.24	108.78 ± 16.26	0.348
pre-PWD_{aVL}(ms)	90.76 ± 18.84	96.02 ± 18.76	0.097
pre-PWD_{aVF}(ms)	108.64 ± 16.31	107.89 ± 18.35	0.789
pre-PWD_{V1}(ms)	99.29 ± 18.21	103.42 ± 22.22	0.199
pre-PWD_{V2}(ms)	100.37 ± 18.60	106.27 ± 17.90	0.058
pre-PWD_{V3}(ms)	108.31 ± 15.99	113.22 ± 13.36	0.060
pre-PWD_{V4}(ms)	111.61 ± 15.35	114.80 ± 16.31	0.223
pre-PWD_{V5}(ms)	112.32 ± 14.96	115.93 ± 14.12	0.147
pre-PWD_{V6}(ms)	111.54 ± 16.16	115.80 ± 12.85	0.103
pre-Pmax(ms)	124.21 ± 12.03	128.84 ± 12.68	0.024 *
pre-Pd(ms)	45.58 ± 13.16	51.29 ± 15.09	0.013 *
pre-P-index(ms)	13.87 ± 4.41	13.8 ± 4.59	0.959
pre-PWA_I(mV)	0.07 ± 0.02	0.07 ± 0.03	0.578
pre-PWA_{II}(mV)	0.11 ± 0.04	0.11 ± 0.04	0.895
pre-PWA_{III}(mV)	0.07 ± 0.03	0.07 ± 0.03	0.476
pre-PWA_{aVR}(mV)	0.09 ± 0.03	0.09 ± 0.03	0.688
pre-PWA_{aVL}(mV)	0.04 ± 0.02	0.04 ± 0.02	0.800
pre-PWA_{aVF}(mV)	0.09 ± 0.04	0.09 ± 0.03	0.915
pre-PWA_{V1}(mV)	0.05 ± 0.03	0.06 ± 0.03	0.074
pre-PWA_{V2}(mV)	0.05 ± 0.03	0.06 ± 0.03	0.462
pre-PWA_{V3}(mV)	0.06 ± 0.03	0.06 ± 0.03	0.899
pre-PWA_{V4}(mV)	0.06 ± 0.03	0.07 ± 0.03	0.705
pre-PWA_{V5}(mV)	0.06 ± 0.02	0.07 ± 0.02	0.483
pre-PWA_{V6}(mV)	0.06 ± 0.02	0.06 ± 0.03	0.612
pre-P-area(ms.mV)	6.35 ± 2.55	6.51 ± 2.14	0.695
pre-Ptf_{V1}(mm.s)	0.03 ± 0.02	0.04 ± 0.02	0.028 *
pre-PWN(%)	50(29.8%)	10(22.2%)	0.417
pre-PWN counts(N)	1.27 (2.26)	1.09 (2.22)	0.625
pre-pIAB(%)	57(33.9%)	21(46.7%)	0.161
pre-aIAB(%)	6(3.6%)	2(4.4%)	1

*$P < 0.05$

Table 3 Comparison of postoperative ECG P wave parameters

P wave parameters	No-recurrence group (*N* = 168)	Recurrence group (*N* = 45)	*P* value
post-HR(times/min)	78.62 ± 11.95	77.56 ± 12.88	0.601
post-QRS interval(ms)	80.64 ± 14.40	76.85 ± 21.11	0.160
post-QTc interval(ms)	422.73 ± 25.03	419.51 ± 31.46	0.470
post-PR interval(ms)	151.11 ± 21.18	155.40 ± 21.58	0.231
post-PWD_I(ms)	102.86 ± 16.48	108.02 ± 13.44	0.054
post-PWD_{II}(ms)	105.70 ± 16.56	117.13 ± 18.94	< 0.001 *
post-PWD_{III}(ms)	98.76 ± 17.36	109.51 ± 19.15	< 0.001 *
post-PWD_{aVR}(ms)	102.62 ± 16.21	107.82 ± 13.93	0.051
post-PWD_{aVL}(ms)	91.48 ± 17.02	92.22 ± 19.64	0.801
post-PWD_{aVF}(ms)	99.98 ± 18.02	110.56 ± 18.67	0.001 *
post-PWD_{V1}(ms)	99.74 ± 16.45	105.18 ± 16.67	0.051
post-PWD_{V2}(ms)	100.51 ± 14.60	105.16 ± 14.69	0.059
post-PWD_{V3}(ms)	103.16 ± 14.93	107.98 ± 15.64	0.058
post-PWD_{V4}(ms)	105.33 ± 13.84	109.22 ± 12.81	0.090
post-PWD_{V5}(ms)	107.03 ± 12.22	110.44 ± 12.46	0.099
post-PWD_{V6}(ms)	105.38 ± 14.04	109.60 ± 16.06	0.084
post-Pmax(ms)	119.87 ± 12.51	128.38 ± 13.11	< 0.001 *
post-Pd(ms)	40.52 ± 11.62	50.69 ± 14.36	< 0.001 *
post-P-index(ms)	12.91 ± 3.96	14.05 ± 5.04	0.107
post-PWA_I(mV)	0.07 ± 0.03	0.07 ± 0.03	0.457
post-PWA_{II}(mV)	0.09 ± 0.04	0.10 ± 0.03	0.210
post-PWA_{III}(mV)	0.06 ± 0.03	0.06 ± 0.03	0.379
post-PWA_{aVR}(mV)	0.08 ± 0.03	0.09 ± 0.03	0.220
post-PWA_{aVL}(mV)	0.05 ± 0.03	0.05 ± 0.03	0.756
post-PWA_{aVF}(mV)	0.07 ± 0.03	0.07 ± 0.03	0.476
post-PWA_{V1}(mV)	0.05 ± 0.03	0.05 ± 0.03	0.624
post-PWA_{V2}(mV)	0.07 ± 0.03	0.06 ± 0.03	0.280
post-PWA_{V3}(mV)	0.07 ± 0.03	0.07 ± 0.03	0.696
post-PWA_{V4}(mV)	0.07 ± 0.03	0.07 ± 0.03	0.211
post-PWA_{V5}(mV)	0.06 ± 0.03	0.06 ± 0.03	0.081
post-PWA_{V6}(mV)	0.05 ± 0.02	0.06 ± 0.02	0.297
post-P-area(ms.mV)	4.91 ± 2.38	5.82 ± 2.27	0.022 *
post-Ptf_{V1} Absolute value(mm.s)	0.03 ± 0.02	0.04 ± 0.02	< 0.001 *
post-PWN(N)(%)	34(20.2%)	7(15.6%)	0.621
post-PWN counts(N)	0.90 ± 1.94	0.91 ± 2.49	0.984
post-pIAB(%)	35(20.8%)	21(46.7%)	0.001 *
post-aIAB(%)	3(1.8%)	2(4.4%)	0.623

*$P < 0.05$

($P < 0.001$). Among these, the differences in PWD in lead II, III, and aVF were statistically significant, while differences in PWD in other leads were not statistically significant (sTable S3, sFigure S3). Also, differences in PWA in the same leads between the non-recurrence group and the recurrence group were not statistically significant (sTable S4, sFigure S4).

Changes in P wave parameters before and after ablation

Further analysis of the changes in P-wave parameters (indicates as Delta-) before and after ablation in the non-recurrence and recurrence groups revealed significant differences in Delta-Pmax ($P = 0.019$), Delta-PtfV1 absolute value ($P = 0.03$), Delta-Pd ($P = 0.048$), Delta-PWDII ($P = 0.02$), Delta-PWDIII ($P = 0.006$), Delta-PWDaVF ($P = 0.001$), and Delta-PWDV5 ($P = 0.016$). No significant differences were found in other P-wave parameters such as Delta-HR, Delta-QRS interval, Delta-QTc interval, Delta-PR interval, Delta-P-area, Delta-P-index, Delta-PWDI, Delta-PWDaVR, Delta-PWDaVL, Delta-PWDV1, Delta-PWDV2, Delta-PWDV3, Delta-PWDV4, Delta-PWDV6, Delta-PWAV6 and Delta-PWN (Fig. 1, sTable S5).

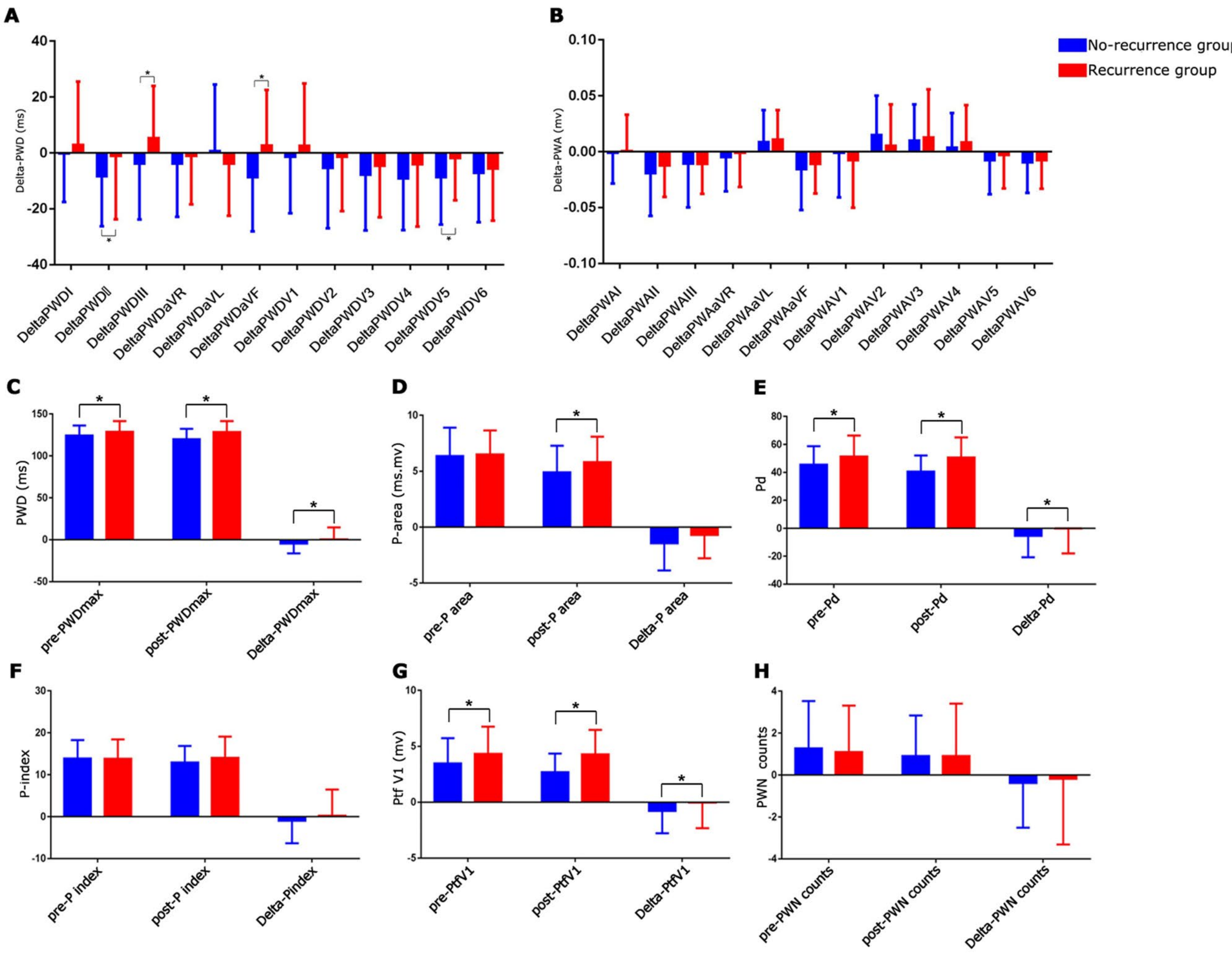

Fig. 1 Preoperative and postoperative changes of parameters: **A** comparison between the PWD values of the ECG for the 12 leads prior to and following catheter ablation. **B** Comparing the 12-lead ECG's PWA values prior to and following catheter ablation. **C** Variations in Pmax value during and after surgery. **D** P-area value changes prior to and following surgery. **E** variations in Pd values prior to and following surgery. **F** preoperative and postoperative P-index value changes. **G** preoperative and postoperative PtfV1 absolute value changes. **H** preoperative, and postoperative PtfV1 value changes. *$P < 0.05$

ROC curve analysis

The ROC curves for the differential P-wave parameters obtained from the statistical analysis were drawn, and the area under the ROC curve (AUC) was recorded. The optimal cutoff values were identified as follows: post- PWDII at 118.5 ms, post- PWDIII at 103.5 ms, and post- PWDaVF at 116.5 ms. The PWD of the 12 leads was significantly lower post-catheter ablation compared to pre-ablation, with significant differences observed in the inferior wall leads II, III, and aVF. The optimal cutoff values for Delta-PWDII, Delta-PWDIII, and Delta- PWDaVF were −5.5 ms, -13.5 ms, and −8.5 ms, respectively. The absolute values of Delta-PWD (II, III, aVF leads), Delta-Pmax, Delta-Pd, and Delta- PtfV1 in postoperative P-wave parameter changes were significantly lower in the recurrent atrial fibrillation group than in the non-recurrent group. The P-index, a new characteristic indicator of the heterogeneity of action potential conduction in the atrium, had optimal cutoff values for Pre-Pmax at 127.5 ms, post-Pmax at 121.5 ms, and Delta-Pmax at 7.5 ms. P-wave dispersion (Pd), reflecting the heterogeneity of electrical activity in different parts of the atrium, typically has a value of <40 ms. The optimal cutoff values for Pre-Pd, post-Pd, and Delta-Pd were 31.5 ms, 47.5 ms, and −2.5 ms, respectively. The absolute value of PtfV1, defined as the product of the amplitude and duration of the negative P wave terminal in lead V1, with >0.03 mm·s considered abnormal, had optimal cutoff values of pre- PtfV1 at 0.025 mm·s, post-PtfV1 at 0.043 mm·s, and Delta- PtfV1 at 0.011 mm·s. The AUC for the post-P wave area was 0.613, with an optimal cutoff value of 3.22 ms·mV, a specificity of 31.5%, and a sensitivity of 93.3% (Fig. 2).

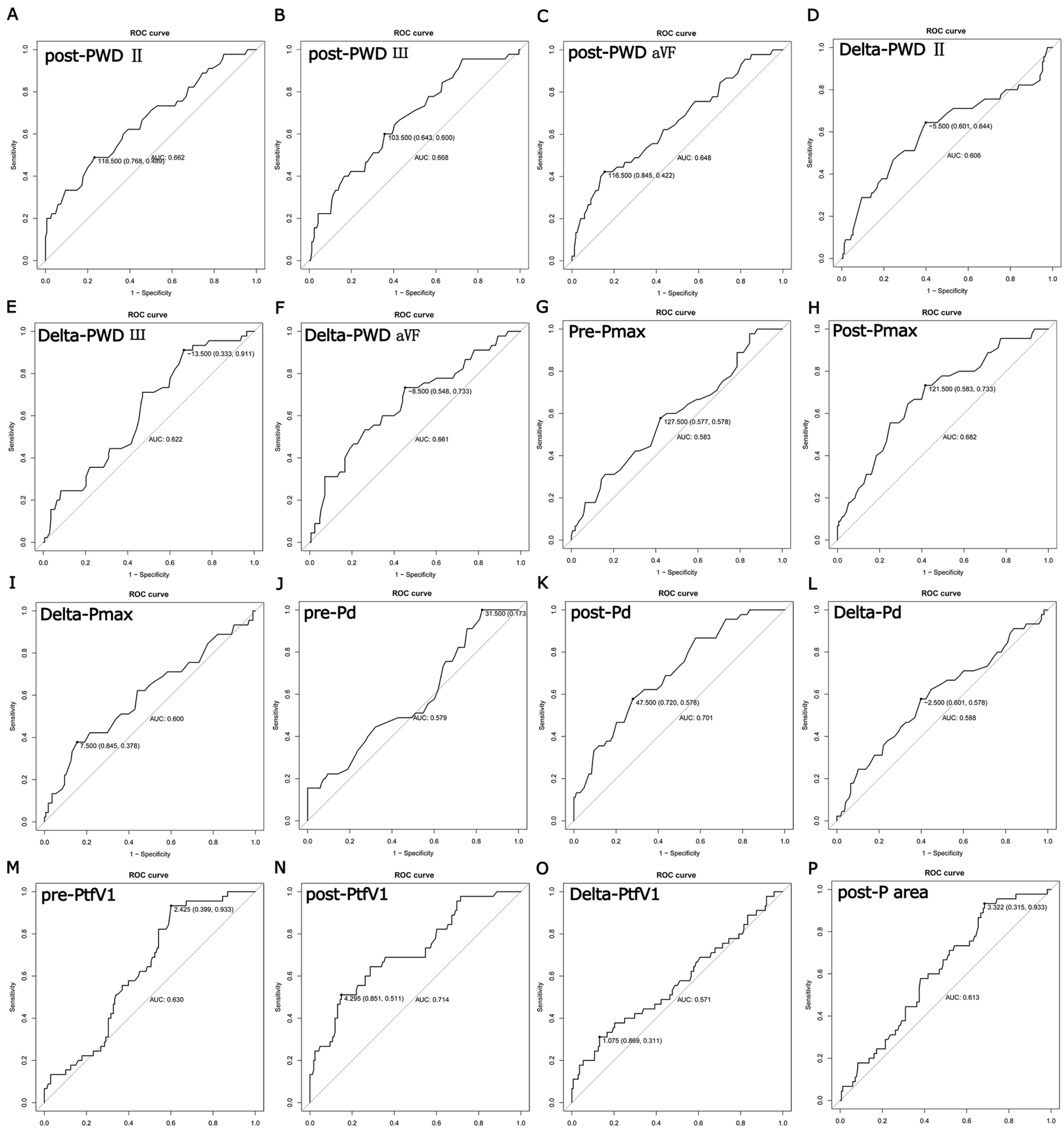

Fig. 2 ROC curve analysis of post-PWD and Delta-PWD following catheter ablation. (**A**) post-PWDII ROC curve. (**B**) post-PWDIII ROC curve. (**C**) post-PWDaVF ROC curve. (**D**) Delta-PWDII ROC curve; (**E**) Delta-PWDIII ROC curve; (**F**) Delta-PWDaVF ROC curve. (**G**) ROC curve analysis of pre-Pmax. (**H**) ROC curve of post-Pmax. (**I**) ROC curve of Delta-Pmax. (**J**) ROC curve analysis of pre-Pd. **K** ROC curve analysis of post-Pd. **L** ROC curve analysis of Delta-Pd. **M** ROC curve analysis of the absolute value of pre-PtfV1. **N** ROC curve analysis of the absolute value of post-PtfV1. **O** ROC curve analysis of the absolute value of Delta-PtfV1. **P** The post-P-area area under the ROC curve for atrial fibrillation ablation recurrence prediction

Single-factor logistic regression analysis

By using the differential P-wave parameters obtained from the above statistical analysis and combined with the optimal critical values from the ROC curve, a single-factor logistic regression analysis was performed (Table 4). It was found that the preoperative P-wave parameter related to postoperative recurrence of PAF were pre-PtfV1 absolute values ≥ 0.025 mm·s ($HR = 3.55$, $P < 0.05$). The Postoperative P-wave parameters related to postoperative recurrence of PAF include post PWDII,

Table 4 Univariate Logistic regression of ECG P-wave parameters

Variable	HR (95%CI)	*P*-value
pre-Pmax ≥ 127.5ms	1.87(0.97,3.68)	0.06
pre-Ptf_{V1} Absolute value (mm.s) ≥ 0.025	3.55(1.63,8.63)	0.00 *
pre-Pd ≥ 40ms	1.42(0.69,3.14)	0.36
post-PWD_{II}≥118.5ms	3.16(1.59,6.31)	0.00 *
post-PWD_{III}≥103.5ms	2.70(1.39,5.37)	0.00 *
post-PWD_{aVF}≥116.5ms	3.99(1.93,8.27)	0.00 *
post-Pmax ≥ 117.5ms	2.93(1.38,6.82)	0.01 *
post-Ptf_{V1} absolute value (mm.s) ≥ 0.043	5.98(2.92,12.45)	0.00*
post-Pd ≥ 47.5ms	3.52(1.79,7.04)	0.00 *
post-P-area(ms.mV) ≥ 3.322	6.45(2.22,27.45)	0.00 *
Delta-PWD_{II}≥-5.5ms	2.73(1.39,5.52)	0.00 *
Delta-PWD_{III}≥-13.5ms	5.12(1.95,17.68)	0.00 *
Delta-PWD_{aVF}≥-8.5ms	3.33(1.65,7.13)	0.00 *
Delta-Pmax ≥ 7.5ms	3.32(1.58,6.90)	0.00 *
Delta-Ptf_{V1} Absolute value ≥ 0.011(mm.s)	2.70(1.21,5.87)	0.01 *
Delta-Pd≥-2.5ms	2.06(1.06,4.07)	0.03 *

*$P < 0.05$

post PWDIII, post PWDaVF, post Pmax, absolute post PtfV1 value, post Pd and post P-area. Changes in P-wave parameters before and after surgery related to postoperative recurrence included Delta- PWDII ≥ -5.5 ms (HR = 2.73, $P < 0.05$), Delta-PWDIII ≥ -13.5 ms (HR = 5.12, $P < 0.05$), Delta-PWDaVF ≥ -8.5 ms (HR = 3.33, $P < 0.05$), Delta Pmax ≥ 7.5 ms, (HR = 3.32, $P < 0.05$), Delta PtfV1 absolute value ≥ 0.011 mm·s (HR = 2.70, $P < 0.05$), and Delta Pd ≥ -2.5 ms (HR = 2.06, $P < 0.05$. The forest plot of the differential P-wave indexes obtained from the above statistical analysis was drawn (Fig. 3).

Establishing a Nomogram model

Based on the logistic regression results, an individualized columbaric prediction model was established using R software by incorporating significant P-wave parameters for predicting the risk of recurrence (Fig. 4). This model includes 16 independent risk factors. The application of the model is as follows: By using the Nomogram map, the score of each predictor was calculated. The scores of all variables were then totaled to obtain the total score. Finally, the probability of predicting the risk of recurrence was determined by examining the corresponding points on the recurrence risk axis after PAF ablation.

Assessment of prediction effectiveness of the Nomogram model

The calibration curve was used to assess the consistency between predicted risk and observed outcomes. The Hosmer-Lemeshow test indicated good calibration of our Nomogram model, with X^2 = 0.054 and $P > 0.05$. Visually, the calibration curve closely aligned with the reference line, indicating accurate prediction of recurrence risk after catheter ablation. For internal validation of the model, the Bootstrap method was used with 1000 resamples. The sensitivity and specificity of the nomogram model were 89.3% and 80%, respectively. The AUC was 0.880, with an optimal cutoff value of 480.99. Clinical DCA demonstrated that the model achieved significantly enhanced predictive performance and provided enhanced clinical benefits (Fig. 5).

Discussion

Studies have shown that both electrical remodeling and structural changes in the atrium are pivotal in initiating and sustaining AF [11]. However, some studies indicate that electrical remodeling may precede structural remodeling. P wave parameters like PWD, Pd, PtfV1, and other ECG markers can indirectly indicate the extent of atrial electrical remodeling and are readily measurable [12–15]. In patients with PAF, abnormalities in P wave parameters on ECG often precede detectable pathological changes in the atria observed via cardiac imaging modalities like color Doppler ultrasound and cardiac magnetic resonance imaging [16]. Thus, identifying P wave parameters associated with AF recurrence post-catheter ablation and developing predictive models can help clinicians in early identification of high-risk patients and selection of appropriate therapeutic strategies. In this study, we found that absolute values of PWD, Pmax, Pd, and PtfV1 were significantly higher in the recurrence group compared to the non-recurrence group. Also, the proportion of partial Inter Atrial Block (pIAB) and advanced Inter Atrial Block (aIAB) was higher in the recurrence group. These findings are attributed to atrial chamber remodeling following AF onset, which leads to atrial dilation and increased fibrosis of atrial muscle due to prolonged AF episodes. These anatomical changes consequently affect electrophysiological properties, including prolonged action potential conduction time, reduced conduction velocity, shortened effective refractory period, increased conduction inhomogeneity, and greater dispersion of refractory periods within the atrial tissue. These changes are well-reflected by changes in P wave parameters, particularly manifesting as increased PWD and Pd. Numerous studies have demonstrated that changes in PWD and Pd are correlated with AF recurrence following ablation procedures. Logistic regression analysis further indicated that pre-procedural Pmax, pre-Pd, and pre-PtfV1 values were predictive of postoperative recurrence of PAF. Therefore, when assessing the risk of PAF recurrence post-ablation, it is crucial to assess the absolute values of pre-procedural Pmax, pre-Pd, and pre-PtfV1.

Multiple studies have consistently reported that post-catheter ablation, PWD is significantly reduced compared to preoperative levels, with a more pronounced decrease observed in patients without AF recurrence compared to those with recurrence. [10, 17, 18] Our study

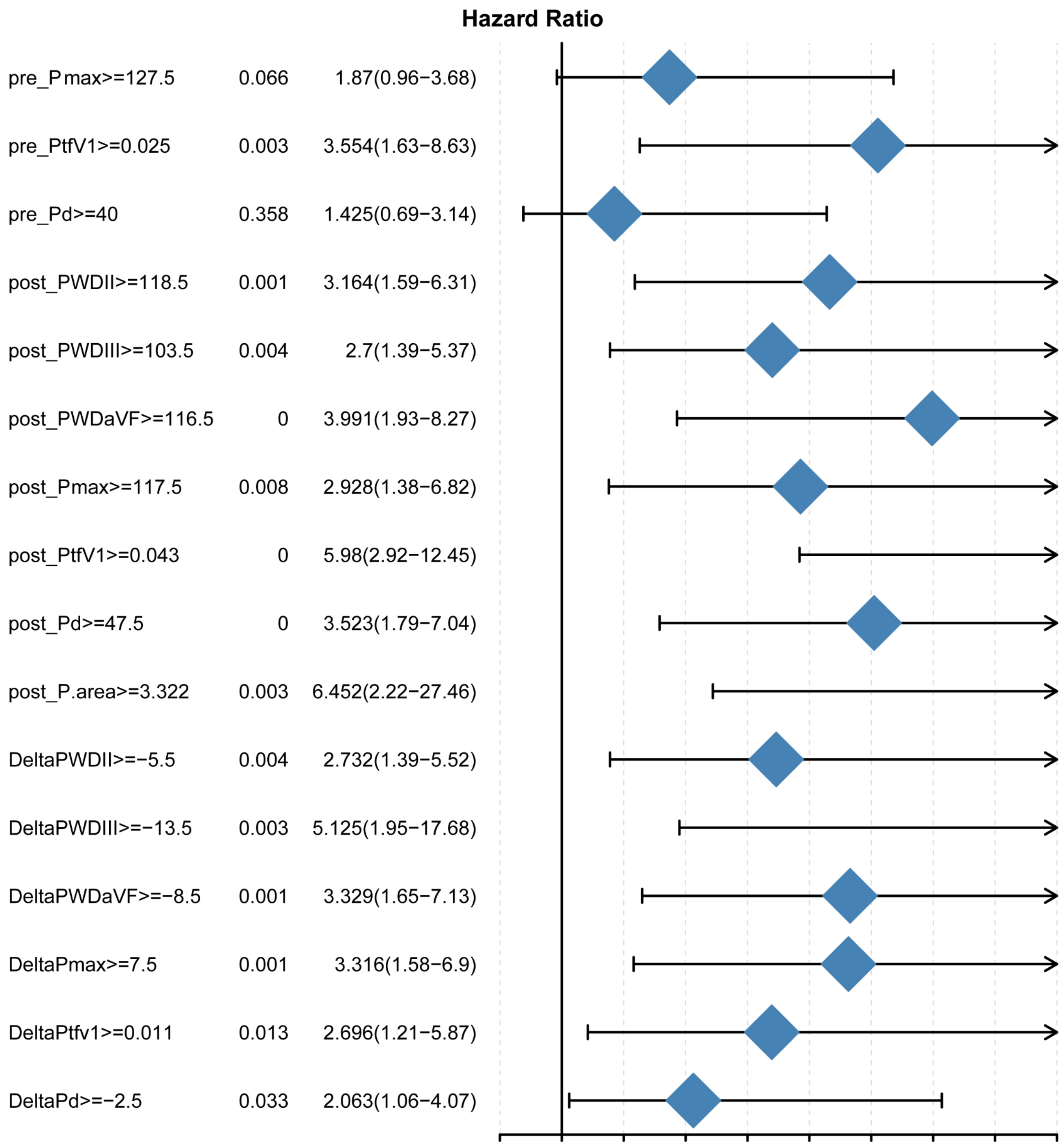

Fig. 3 Recurrence risk ratio following atrial fibrillation as indicated by ECG P wave parameters

corroborates these findings. Logistic regression analysis revealed that post-ablation P-wave parameters like PWD, Pmax, Pd, P-area, PtfV1, and pIAB, were significantly lower than pre-ablation values. Specifically, post-PWD was notably decreased compared to pre-PWD, with significant differences observed in leads II, III, and aVF. The absolute changes in PWD (in leads II, III, aVF), Pmax, Pd, and PtfV1 post-ablation were significantly smaller in patients who experienced AF recurrence compared to those who did not. The generation of atrial action potentials by the pulmonary vein musculature constitutes a major component of the ECG P wave and contributes to prolonged PWD. Therefore, it is hypothesized that catheter ablation of the pulmonary vein vestibule blocks this action potential generation, resulting in shortened PWD. The distinct changes observed in leads II, III, and aVF

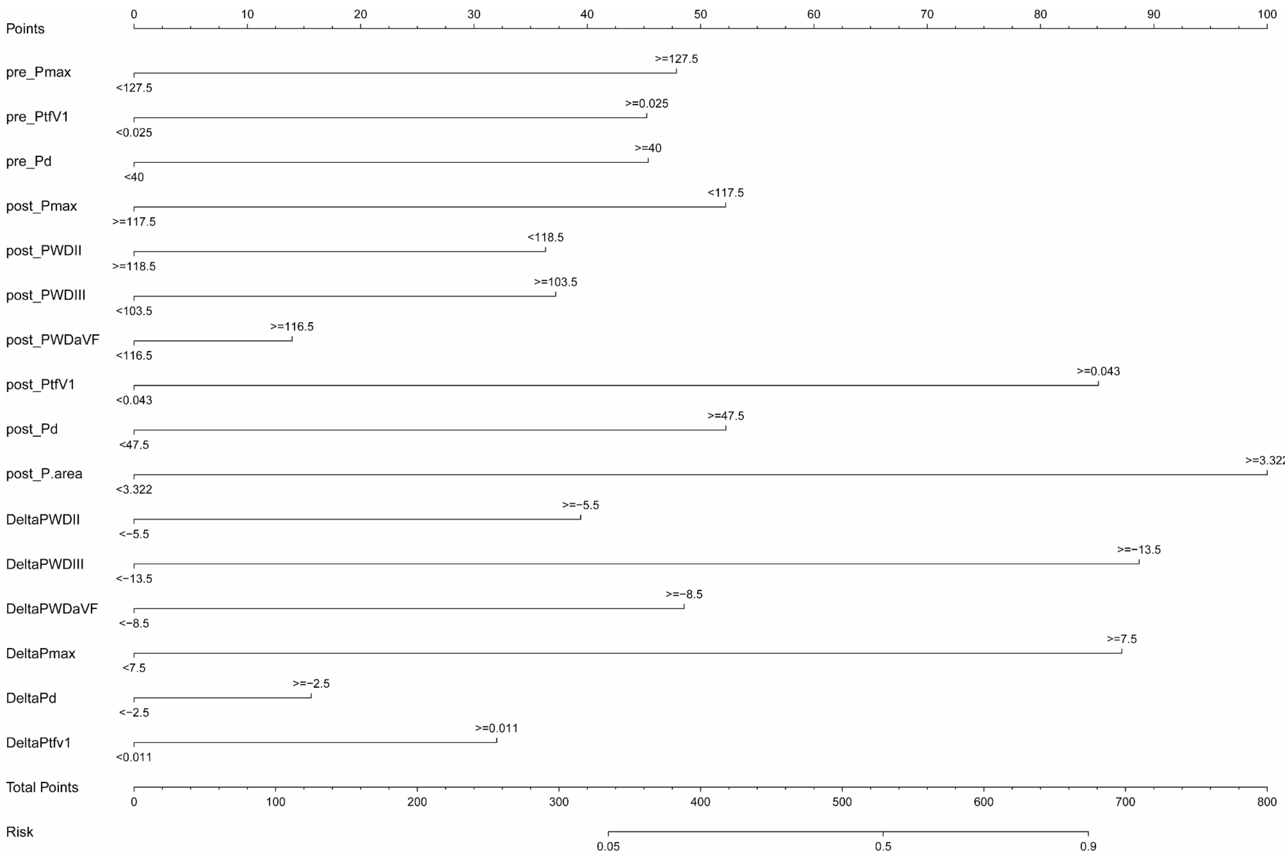

Fig. 4 ECG P wave parameters used to establish the nomogram model

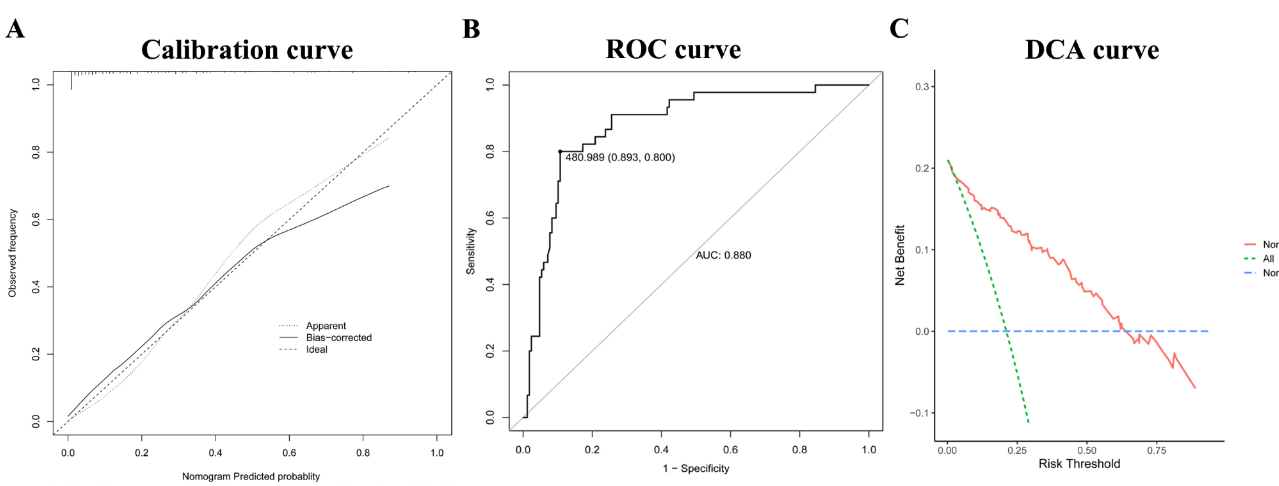

Fig. 5 ECG P wave parameters predicted and assessed using a nomogram. **A** Calibration curve. **B** ROC curve. **C** DCA curve

postoperatively may be attributed to the directional pattern of atrial depolarization, which shifts from right to left, resulting in a leftward and downward frontal vector at approximately + 58°, aligning closely with these specific leads. Furthermore, our study noted a decrease in the proportion of abnormal P-wave indexes, Pd, and P-wave area post-ablation compared to preoperative levels. However, no significant changes were observed in the overall changes of these indexes, nor was their relationship with AF recurrence further investigated [19].

The increase in Pd is attributed to the dispersion of atrial myocytes during depolarization or irregular timing of action potentials, which are critical factors contributing to the initiation and perpetuation of AF [20]. Elevated Pd heightens the susceptibility to atrial arrhythmias and is commonly used to forecast AF recurrence. As indicated by conducted studies, preoperative Pd values were significantly higher in the recurrence group compared to the non-recurrence group, with multivariate analysis identifying a diagnostic threshold of preoperative Pd ≥ 46 ms for predicting AF recurrence. Furthermore, postoperative Pd values were observed to be higher in the AF recurrence group when compared to the non-recurrence group, accompanied by significantly smaller reductions in Delta-Pd in the recurrence group. Post-Pd and Delta-Pd are recognized as predictive factors for AF recurrence following ablation for PAF.

It is reported that significantly higher P-wave index values in patients who developed AF following Radio Frequency Catheter Ablation (RFCA) compared to those who did not experience AF [19]. As indicated in some studies, a prolonged P-wave index is associated with an increased risk of AF recurrence after electrical cardioversion. Also, both P-wave duration and dispersion are indicators of conduction delay and heterogeneity within the atrium, providing predictive value for AF recurrence [12, 13]. However, in our study, we did not detect significant differences in either the P-index or its change following ablation. We hypothesize that this lack of significance may stem from the minimal impact on the dispersion of the effective atrial refractory period due to the electrical isolation of the pulmonary veins during catheter ablation.

It has been reported that PWA in lead I ≤ 0.1 is independently associated with clinical recurrence of AF after ablation [21]. Also, a scoring system incorporating abnormal P-wave voltages has proven useful in predicting new-onset AF, with P-wave amplitude < 0.1 mV in lead I independently linked to AF recurrence. Notably, P-wave amplitude in lead I reveals a linear association with left atrial voltage and conduction velocity, indicating its role in assessing electroanatomic remodeling related to AF [22]. As indicated in some studies, low P-wave amplitude in lead I is an independent predictor of AF recurrence following catheter ablation for PAF, reflecting structural changes like left atrial enlargement that may change the relationship with Bechmann's bundle direction parallel to lead I. This structural change can lead to an increased angle between them and uneven conduction, thereby reducing P-wave amplitude in lead I. However, in our study, we did not find significant differences in postoperative P-wave amplitude and its change between the recurrent and non-recurrent groups. This deviation from expected outcomes may be attributed to limitations in sample size.

Abnormal P-wave area is indicative of left atrial enlargement and structural abnormalities [3, 23], and it serves as an independent risk factor for AF [24]. In this study, postoperative P-wave area was significantly larger in the recurrent AF group compared to the non-recurrent group, and notably smaller than preoperative levels. This observation is attributed to changes in the duration and amplitude of the P wave on ECG, influenced by the combined effects of catheter ablation, which includes atrial myocyte destruction and modification.

The absolute value of PtfV1 refers to the product of the amplitude and duration of the terminal negative P wave in lead V1, with values greater than 0.03 mm·s being classified as abnormal. In cases of left atrial enlargement, the ECG often reveals not only a longer P-wave duration but also a more pronounced negative P wave component in lead V1. Each standard deviation increase in the P-wave terminal force in lead V1 is associated with a 23% increased risk of AF. Most scholars agree that catheter ablation, which isolates the pulmonary vein muscle sleeve potential, results in a decreased absolute value of PtfV1 compared to pre-ablation levels [25]. Our findings indicated that the pre-ablation absolute value of PtfV1 was higher in the recurrent AF group than in the non-recurrent group. Also, the post-ablation absolute value of PtfV1 was lower than pre-ablation values and was closely related to AF recurrence. Logistic regression analysis identified post-ablation PtfV1 and the change in PtfV1 (Delta-PtfV1) as significant predictors of postoperative AF recurrence.

P-wave parameters obtained from surface ECG effectively reflect the changes in atrial electrical remodeling in patients with AF, which are closely related to the occurrence, progression, and recurrence of AF after catheter ablation. However, relying on a single P-wave parameter is insufficient to comprehensively capture the changes in atrial electrical remodeling. Therefore, this study considered the risk weight of each indicator and innovatively integrated the P-wave parameters to construct a nomogram, which offers greater sensitivity and specificity for predicting the recurrence risk after ablation of PAF. Among these parameters, PWD, Pd, and PWA are key electrocardiographic indicators related to AF and its recurrence [26]. Specifically, Pd and PWD reflect atrial conduction discontinuity and heterogeneity, and numerous clinical studies across various fields have documented their effects on AF [9, 27, 28].

The nomogram model integrates various risk factors and visually presents the results of regression analysis, intuitively predicting individual disease risk [29]. However, there has been no reported nomogram study specifically predicting the recurrence risk in patients with PAF after ablation based on P-wave parameters. In this study, we constructed a nomogram model to predict the recurrence risk in PAF patients post-ablation by using the analysis results from the regression model. The calibration curve and DCA demonstrated that the predicted risk closely aligned with the observed outcomes, indicating good predictive performance of the model. The nomogram model integrates the P-wave parameters of the body surface electrocardiogram, reflecting the electrophysiological changes of the heart before and after radiofrequency ablation of paroxysmal atrial fibrillation, and visualizing the risk of recurrence of atrial fibrillation after ablation, providing significant clinical benefits.

Conclusion

Body surface ECG P-wave parameters can serve as valuable reference factors for predicting the recurrence of PAF in patients following catheter ablation. The nomogram model established based on these P-wave parameters provides an effective tool for predicting PAF recurrence post-ablation.

Limitations

This study was a single-center retrospective study with an insufficient sample size and a large time span of selected patients, and no comparative analysis was conducted in different ablation methods. Therefore, it cannot be ruled out that different ablation methods and other factors may have an impact on the change of P-wave parameters and the recurrence rate of atrial fibrillation. In addition, no further intracardiac electrophysiological examination was performed for patients with late recurrence of atrial fibrillation after ablation, and the source of the recurrence could not be determined.

Abbreviations

PAF	Paroxysmal atrial fibrillation
AF	Atrial fibrillation
ECG	Electronic cardiogram
ESC	European Society of Cardiology
NYHA	New York Heart Association
PWD	P Wave Duration
PWA	P Wave Amplitude
Ptf	P Wave Terminal Force
Pd	P Wave Dispersion
P-index	P Wave Index
P-area	P Wave Area
Pmax	Maximum P Wave Duration
PWN	P Wave Notch
IAB	Inter Atrial Block
pIAB	Partial Interatrial Block
aIAB	Advanced Interatrial Block
pre-PWD	P wave duration of pre-operation
post-PWD	P Wave Duration of postoperation
Delta-PWD	Delta P Wave Duration
Delta-PWA	Delta P WaVe Amplitude
Delta-Ptf	Delta P Wave Terminal Force
LAD	Left Atrial Diameter
LVEF	Left Ventricular Ejection Fraction
LVEDD	Left Ventricular End-diastolic Diameter
AAD	Antiarrhythmic drugs
ROC	Receiver Operating Characteristic Curve
DCA	Decision Curve Analysis
TC	Serum total cholesterol
TG	Triglyceride
NT-BNP	N-terminal pro-B-type Natriuretic Peptide
ACEI	Renin-angiotensin Converting Enzyme Inhibitor
ARB	Angiotensin Receptor Blocker
SC	Serum Creatinine
BMI	Body Mass Index
TSI	Transient Ischemic Attack
HF	Heart Failure
MI	Myacardial Infarction
CKD	Chronic Kidney Disease
VTE	Venous Thrombo Embolism
AUC	Area Under Curve
RFCA	Radio Frequency Catheter Ablation

Supplementary Information

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Supplementary Material 1

Supplementary Material 2

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Author contributions

Conception and design of the research: Li-juan Yu, Fei-Long Zhang. Acquisition of data: Li-juan Yu, Zhe Xu. Statistical analysis: Li-juan Yu, Zhe Xu, Ke-Zeng Gong. Writing of the manuscript: Li-juan Yu, Ke-Zeng Gong. Analysis and interpretation of the data: Xue-Hai Chen, Ke-Zeng Gong. Critical revision of the manuscript for intellectual content: Li-juan Yu, Xue-Hai Chen, Fei-Long Zhang. All authors read and approved the final draft.

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Data availability

All data generated or analysed during this study are included in this article. Further enquiries can be directed to the corresponding author.

Declarations

Ethics approval and consent to participate

This study was conducted with approval from the Ethics Committee of Fujian Medical University Union Hospital. This study was conducted in accordance with the declaration of Helsinki. Written informed consent was obtained from all participants.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Author details

[1]Department of Cardiology, Fujian Medical University Union Hospital, Fujian Heart Medical Center, Fujian Institute of Coronary Heart Disease, Fujian Clinical Medical Research Center for Heart and Macrovascular Disease, Fuzhou 350001, China
[2]Department of Electrocardiography, Fujian Provincial Governmental Hospital, Fuzhou 350001, China

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