

# Comparative Evaluation of II Prognostic Scores for Atrial Fibrillation Recurrence After Pulmonary Vein Isolation in Non-Paroxysmal AF: A Retrospective Comparative Analysis

Lin-Xin Guan, Xue-Hai Chen, Zhe Xu, Ke-Zeng Gong, Fei-Long Zhang

Department of Cardiology, Fujian Medical University Union Hospital; Fujian Cardiovascular Medicine Center; Fujian Institute of Coronary Artery Disease; Fujian Cardiovascular Research Center; Fujian Medical University Heart Center, Fuzhou, 350001, People's Republic of China

Correspondence: Fei-Long Zhang, Department of Cardiology, Fujian Medical University Union Hospital; Fujian Cardiovascular Medicine Center; Fujian Institute of Coronary Artery Disease; Fujian Cardiovascular Research Center; Fujian Medical University Heart Center, No. 29 of Xinquan Road, Gulou District, Fuzhou, 350001, People's Republic of China, Tel +86 13365910662, Fax +86 091 83322156, Email cardizhang@163.com

**Objective:** Pulmonary vein isolation (PVI) remains the cornerstone of catheter ablation for atrial fibrillation (AF); however, a substantial proportion of patients with non-paroxysmal AF (non-PAF) experience recurrence following ablation. With numerous prognostic models available to predict recurrence, the aim of this study is to compare the predictive performance of multiple scoring systems in patients with non-PAF undergoing PVI as a standalone procedure.

**Methods:** A retrospective analysis was conducted involving 166 patients with non-PAF (22.3% female; mean age  $60 \pm 9$  years) who underwent initial PVI alone. Clinical data, including transthoracic echocardiography and either cardiac computed tomography or transesophageal echocardiography, were collected. The evaluated prognostic scoring systems included APPLE, BASE-AF<sub>2</sub>, C<sub>2</sub>HEST, CAAP-AF, CHA<sub>2</sub>DS<sub>2</sub>-VASc, CHADS<sub>2</sub>, DR-FLASH, HATCH, MB-LATER, PAT<sub>2</sub>C<sub>2</sub>H, and SCALE-CryoAF.

**Results:** Recurrence of AF following a 90-day blanking period was observed in 41 individuals (24.7%), including 24 (51.8%) in the cryo-balloon ablation (CBA) subgroup and 17 (48.2%) in the radiofrequency catheter ablation (RFCA) subgroup. Among the evaluated models, BASE-AF<sub>2</sub> (AUC = 0.666, 95% CI: 0.572–0.759,  $p = 0.001$ ), MB-LATER (AUC = 0.734, 95% CI: 0.646–0.821,  $p < 0.001$ ), and SCALE-CryoAF (AUC = 0.702, 95% CI: 0.600–0.804,  $p < 0.001$ ) demonstrated superior prognostic performance for recurrence. After propensity score matching, MB-LATER (AUC = 0.734, 95% CI: 0.570–0.899,  $p = 0.019$ ) was identified as the most effective predictor of recurrence in the CBA subgroup, while BASE-AF<sub>2</sub> (AUC = 0.758, 95% CI: 0.578–0.937,  $p = 0.013$ ) indicated superior predictive accuracy in the RFCA subgroup.

**Conclusion:** The BASE-AF<sub>2</sub>, MB-LATER, and SCALE-CryoAF scoring systems demonstrated enhanced prognostic use for predicting AF recurrence following PVI alone in patients with non-PAF. MB-LATER exhibited superior performance in those treated with CBA, while BASE-AF<sub>2</sub> was more predictive for those who underwent RFCA.

**Keywords:** catheter ablation, non-paroxysmal atrial fibrillation, pulmonary vein isolation, risk score

## Introduction

Atrial fibrillation (AF) is an independent risk factor for stroke, heart failure, cardiovascular disease, and mortality. The EAST-AFNET 4 study demonstrated that rhythm control strategies offer the benefits of symptom relief, quality of life improvement, and reduction of adverse clinical outcomes.<sup>1</sup> Meanwhile, the CABANA Trial and CASTLE-AF trial have further demonstrated the advantages of catheter ablation over pharmacological therapy in improving the clinical outcomes of patients with AF complicated by heart failure.<sup>2,3</sup> Catheter ablation (CA) is considered the first-line approach for rhythm control, with pulmonary vein isolation (PVI) serving as the central method.<sup>4</sup> In contrast to the high procedural success rates observed in CA for atrioventricular nodal reentrant tachycardia, preexcitation syndrome, and focal atrial



tachycardia, AF particularly the non-paroxysmal subtype is associated with a substantial recurrence rate, presenting a significant therapeutic challenge.<sup>5</sup> So, appropriate selection of AF patients has considerable significance in improving CA outcomes and saving patients' economic expenses. Clinical parameters such as left atrial size, duration of AF, and patient age have been used to estimate the risk of recurrence.<sup>6</sup> Although several prognostic models, including the SCALE-CryoAF and APPLE scores, have been proposed—established based on high-risk factors for recurrence after atrial fibrillation ablation and having identified some populations at high recurrence risk—comparative analyses and external validation remain limited.<sup>7,8</sup> And several previous studies have compared the predictive value of several prognostic models, but the number and scope of models included in these comparisons remain limited.<sup>9,10</sup> In this study, we conducted a comparative evaluation of 11 established AF prognostic scoring systems in patients with non-paroxysmal AF undergoing PVI.

## Methods

### Study Participants

The study population consisted of symptomatic patients with non-paroxysmal atrial fibrillation (non-PAF) who underwent a first CA procedure using a PVI-only strategy at the study institution between January 2016 and November 2021. Informed consent was obtained from all participants prior to treatment, and approval for data analysis was granted by the local ethics committee. The study was conducted in accordance with the principles outlined in the Declaration of Helsinki.

Non-PAF, including persistent and long-term persistent AF, was defined based on the 2020 Guidelines for the management of AF issued by the European Society of Cardiology and the European Association for Cardio-Thoracic Surgery.<sup>2</sup> Prior to the procedure, all participants underwent either transesophageal echocardiography or left atrial computed tomography angiography (CTA) to exclude the presence of thrombus in the left atrium and/or left atrial appendage. Antiarrhythmic medications were discontinued for at least five half-lives prior to the intervention. The study cohort was continuously enrolled to ensure the completeness of clinical data, surgical records, and follow-up information, thereby guaranteeing the representativeness of the population.

Exclusion criteria for this study were: (1) participants deemed intolerant to PVI or in the acute phase of severe pulmonary disease, hepatic failure, uremia, coagulation disorders, severe infection, or advanced heart failure; (2) those with thrombus identified in the left atrium and/or left atrial appendage on preoperative transesophageal echocardiography or CTA; and (3) those with absolute contraindications to, or intolerance of, heparin, vitamin K antagonists, or novel oral anticoagulants.

### RFCA Procedure

The patient was arranged in a supine position on the catheterization table with continuous electrocardiographic monitoring. Following standard disinfection and draping procedures, local anesthesia and moderate-to-deep sedation were administered. A puncture of the right femoral vein was conducted, and an 8F short sheath was inserted. A ten-pole coronary sinus electrode was introduced via the left femoral vein. Dual transeptal punctures were then carried out through the right femoral vein, and two Swartz sheaths were advanced into the left atrium. Heparin sodium (100 µg/kg) was administered following the first transeptal puncture.

An ablation catheter was subsequently advanced into the left atrium, and three-dimensional electro-anatomical mapping was performed using the Carto system to reconstruct three left atrial activation sequence images. Circumferential point-by-point ablation of the ipsilateral pulmonary veins was conducted at 50 W with a saline irrigation rate of 30 mL/min. The procedural endpoint was defined as complete electrical isolation and linear block of the bilateral pulmonary veins.

After a 20-minute observation period, absence of conduction recovery or inducible atrial tachyarrhythmia was confirmed. If sinus rhythm was not restored spontaneously, synchronized electrical cardioversion was performed using 100–150 J. Upon completion of the procedure, all catheters and sheaths were withdrawn, puncture sites were compressed for hemostasis, and sterile gauze was applied.

## CBA Procedure

The patient was arranged in a supine position on the catheterization table. Following disinfection and administration of local anesthesia, puncture of the left femoral vein was performed, and two mapping electrodes were advanced into the coronary sinus and superior vena cava. Subsequent puncture of the right femoral vein facilitated the insertion of a long sheath. Transseptal puncture was then conducted, and a J-wire was guided into the left upper pulmonary vein to allow for sheath advancement into the left atrium.

Heparin was administered at a dose of 100 µg/kg. Bilateral pulmonary venography was subsequently performed. A 28 mm second-generation cryoballoon, along with an Achieve mapping catheter, was delivered to the target region via J-wire exchange. The cryoballoon was sequentially positioned at the antra of the left superior, left inferior, right superior, and right inferior pulmonary veins. Upon achieving adequate vein occlusion, cryoablation was conducted to achieve electrical isolation.

The duration of cryoablation was determined based on the Time to Isolation (TTI): for TTI < 60 seconds, ablation was extended for an additional 120 seconds (with a second ablation also lasting 120 seconds); for TTI ≥ 60 seconds, the catheter was repositioned to improve occlusion before repeating ablation. During right pulmonary vein isolation, diaphragmatic function was continuously monitored by phrenic nerve stimulation. Cryoablation was terminated immediately if diaphragmatic movement was observed to weaken.

In cases where sinus rhythm was not restored following ablation, synchronized electrical cardioversion was performed using 100–150 J. No additional pulmonary vein isolation was conducted beyond the planned sites. All catheters and sheaths were removed upon completion of the procedure, puncture sites were compressed to achieve hemostasis, and sterile gauze was applied.

## Follow-Up

Patients underwent monthly follow-up through outpatient visits or telephone consultations to assess postoperative AF recurrence, with a focus on clinical symptoms such as palpitations, chest discomfort, dyspnea, and fatigue. Routine electrocardiograms (ECGs) were conducted weekly at local healthcare facilities. Patients were advised to undergo a 12-lead ECG or Holter monitoring promptly upon the onset of symptoms.

To discover AF recurrence, 72-hour telemetric ECG monitoring was conducted at 3, 6, and 12 months following the procedure. All follow-up data were systematically recorded. Recurrences were documented if they occurred within 3 months (during the blanking period) or beyond 3 months postoperatively.

The endpoint of follow-up was defined as the detection of AF recurrence, characterized by rapid atrial arrhythmias lasting more than 30 seconds, as identified by either 12-lead ECG or Holter monitoring beyond the 3-month blanking period.

## Risk Score Calculation

Eleven scoring systems were included in this study to evaluate their predictive value for AF recurrence: APPLE,<sup>8</sup> BASE-AF<sub>2</sub>,<sup>11</sup> C<sub>2</sub>HEST,<sup>12</sup> CAAP-AF,<sup>13</sup> CHA<sub>2</sub>DS<sub>2</sub>-VASc,<sup>14</sup> CHADS<sub>2</sub>,<sup>15</sup> DR-FLASH,<sup>16</sup> HATCH,<sup>17</sup> MB-LATER,<sup>18</sup> PAT<sub>2</sub>C<sub>2</sub>H,<sup>19</sup> and SCALE-CryoAF.<sup>7</sup> Several overlapping risk factors were identified among these prognostic models (see [Supplementary Table S1](#)).

The APPLE score comprises of five components: age > 75 years (1 point), persistent AF (1 point), estimated glomerular filtration rate (eGFR) < 60 (mL/min/1.73 m<sup>2</sup>) (1 point), left atrial diameter (LAD) ≥ 43 mm (1 point), and left ventricular ejection fraction < 50% (1 point), with a total score ranging from 0 to 5.

The BASE-AF<sub>2</sub> score includes body mass index (BMI) > 28 kg/m<sup>2</sup> (1 point), LAD > 40 mm (1 point), history of smoking (1 point), recurrence during the blanking period (1 point), AF duration > 6 years (1 point), and non-paroxysmal AF (1 point), with a score range of 0 to 6.

The C<sub>2</sub>HEST score incorporates coronary heart disease (CHD) (1 point), chronic obstructive pulmonary disease (COPD) (1 point), hypertension (HT) (1 point), ≥ 75 years (2 points), congestive heart failure (HF) (2 points), and a history of hyperthyroidism (1 point), resulting in a total score ranging from 0 to 8.

The CAAP-AF score includes CHD (1 point), LAD (0–4 points), age (0–3 points), non-paroxysmal AF (1 point), number of failed antiarrhythmic drugs (AADs) (0–2 points), and female sex (1 point), with a score range of 0 to 12.

The CHA<sub>2</sub>DS<sub>2</sub>-VASc score consists of the following components: congestive HF (1 point), HT (1 point), age 65–74 years (1 point), diabetes mellitus (DM) (1 point), history of transient ischemic attack (TIA) or stroke (2 points), vascular disease (1 point), age ≥ 75 years (2 points), and female sex (1 point), with a total score range of 0 to 8.

The CHADS<sub>2</sub> score includes congestive HF (1 point), HT (1 point), age > 65 years (1 point), DM (1 point), and history of TIA or stroke (2 points), with a score range of 0 to 6.

The DR-FLASH score comprises of DM (1 point), eGFR < 90 mL/min/1.73 m<sup>2</sup> (1 point), persistent AF (1 point), LAD > 45 mm (1 point), age > 65 years (1 point), female sex (1 point), and HT (1 point), resulting in a total score range of 0 to 6.

The HATCH score includes HT (1 point), age > 75 years (1 point), history of TIA or stroke (2 points), COPD (1 point), and congestive HF (1 point), with a total score range of 0 to 6.

The MB-LATER score is based on male sex (1 point), bundle branch block (1 point), LAD ≥ 47mm (1 point), AF type [paroxysmal = 0 point; persistent = 1 point; long-term persistent = 2 points], and recurrence during the blanking period (1 point), with a score range of 0 to 6.

The PAT<sub>2</sub>C<sub>2</sub>H score consists of COPD (1 point), LAD ≥ 45 mm (1 point), HT (1 point), history of TIA or stroke (2 points), and congestive HF (2 points), with a total score range of 0 to 7.

The SCALE-CryoAF score includes structural heart disease (1 point), CHD (3 points), LAD > 43 mm (1 point), left bundle branch block (3 points), recurrence during the blanking period (4 points), and non-paroxysmal AF (1 point), with a total score range of 0 to 15.

## Statistical Analysis

Statistical analyses were conducted using SPSS version 26.0 (IBM Corp., Armonk, NY, USA) and MedCalc version 20.0 (MedCalc Software, Mariakerke, BE). The Kolmogorov–Smirnov test was applied to assess the normality of continuous variables. Variables following a normal distribution are presented as mean ± standard deviation and compared using the Student's *t*-test. Non-normally distributed variables are expressed as medians with interquartile ranges and compared using the Wilcoxon rank-sum test. Categorical variables are reported as n (%) and compared using the chi-squared ( $\chi^2$ ) test.

The area under the receiver operating characteristic curve (AUC) was calculated and compared to assess the prognostic performance of recurrence risk scoring systems for predicting AF recurrence following CA. Calibration of each prognostic model was evaluated using the Hosmer–Lemeshow goodness-of-fit test, and the optimal cutoff value was determined based on the Youden Index. Apply propensity score matching (PSM) to reduce selection bias caused by confounding factors. After PSM between the cryo-balloon ablation (CBA) and radiofrequency catheter ablation (RFCA) subgroups, receiver operating characteristic (ROC) curves were generated to evaluate the prognostic utility of each scoring model in predicting AF recurrence. A value of  $p < 0.05$  was considered statistically significant.

## Result

### Comparison of Overall Prognostic Scoring Systems

#### Baseline Characteristics of Prognostic Scoring Systems

A total of 166 patients with non-PAF who underwent PVI alone were included in this study. The demographic and clinical characteristics of the cohort were as follows: 22.3% were female; the mean age was 60 ± 9 years; the mean BMI was 24.9 ± 3.3 kg/m<sup>2</sup>; 35.5% presented with persistent AF of 24 (5, 48) months' duration; and 48.2% underwent RFCA (see [Supplementary Table S2](#)). Among the 11 calculated recurrence risk scores, BASE-AF<sub>2</sub>, MB-LATER, and SCALE-CryoAF were significantly higher in the recurrence group ( $p < 0.05$ ), as presented in [Table 1](#).

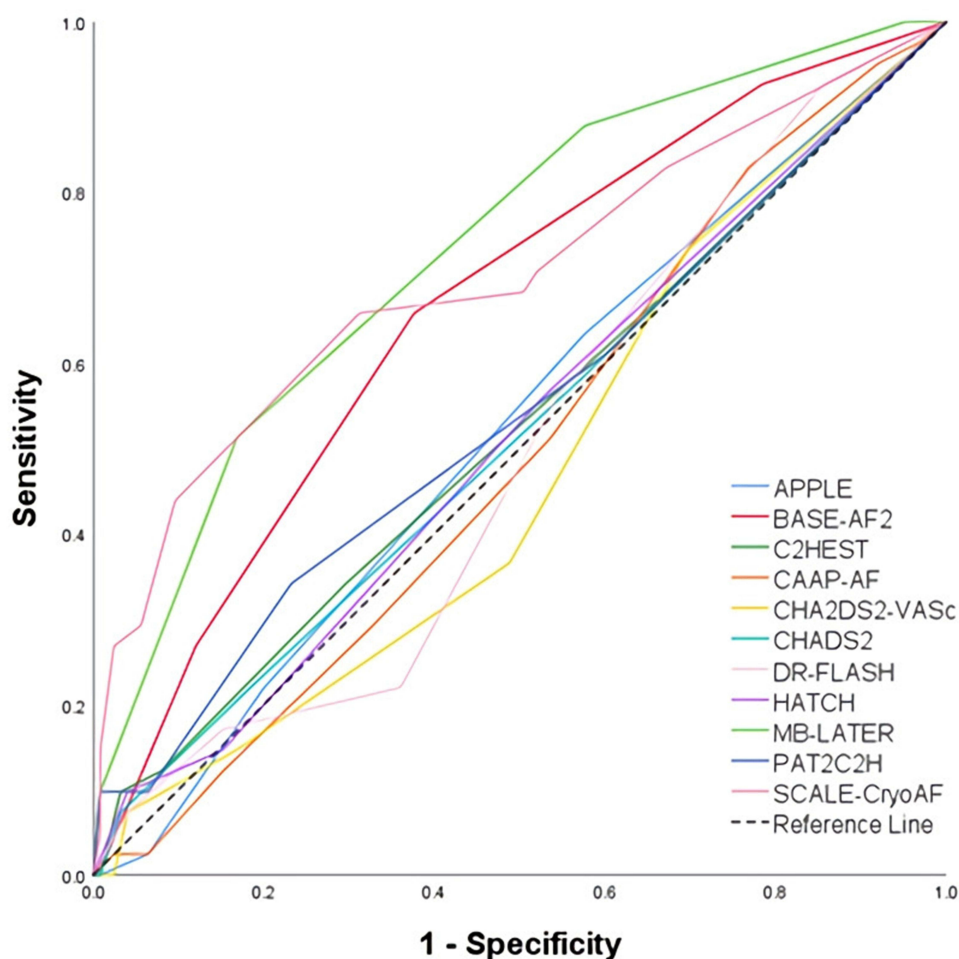
#### Comparing the Prognostic Value of Different AF Recurrence Prognostic Score Systems

ROC curves were generated for all 11 recurrence risk scoring systems ([Figure 1](#)), and the AUC along with the corresponding 95% confidence intervals (CI) were calculated. Optimal cutoff values were determined using the Youden Index ([Table 2](#)). Among the evaluated models, BASE-AF<sub>2</sub> (AUC = 0.666, 95% CI: 0.572–0.759,  $p = 0.001$ ), MB-LATER (AUC = 0.734, 95% CI: 0.646–0.821,  $p < 0.001$ ), and SCALE-CryoAF (AUC = 0.702, 95% CI:

**Table 1** Comparison of AF Prognostic Scoring Systems in the Overall Cohort. [Median, (Minimum, Maximum)]

AF Prognostic Scoring System	All	No AF Recurrence	AF Recurrence	P value
APPLE	2 (1,5)	2 (1,5)	2 (1,4)	0.619
BASE-AF <sub>2</sub>	2 (1,5)	2 (1,5)	3 (1,5)	0.001
C <sub>2</sub> HES <sub>T</sub>	1 (0,5)	1 (0,5)	1 (0,4)	0.613
CAAP-AF	6 (2,10)	6 (2,10)	6 (2,10)	0.948
CHA <sub>2</sub> DS <sub>2</sub> -VASc	1 (0,5)	1 (0,5)	1 (0,4)	0.605
CHADS <sub>2</sub>	1 (0,4)	1 (0,4)	1 (0,3)	0.726
DR-FLASH	3 (1,6)	3 (1,6)	3 (1,6)	0.974
HATCH	1 (0,3)	1 (0,3)	1 (0,3)	0.723
MB-LATER	3 (1,5)	3 (1,5)	3 (2,5)	<0.001
PAT <sub>2</sub> C <sub>2</sub> H	1 (0,4)	1 (0,4)	1 (0,4)	0.419
SCALE-CryoAF	6 (3,12)	5 (3,12)	7 (3,12)	<0.001

0.600–0.804,  $p < 0.001$ ) demonstrated statistically significant prognostic value for predicting AF recurrence ( $p < 0.05$ ). The remaining eight models did not present significant predictive value ( $p > 0.05$ ). Calibration, as assessed by the Hosmer–Lemeshow goodness-of-fit test, indicated acceptable model fit for BASE-AF<sub>2</sub> ( $\chi^2 = 0.493$ ,  $p = 0.781$ ), MB-LATER ( $\chi^2 = 0.241$ ,  $p = 0.886$ ), and SCALE-CryoAF ( $\chi^2 = 8.527$ ,  $p = 0.074$ ).

**Figure 1** Receiver operating characteristic (ROC) curves of 11 atrial fibrillation (AF) recurrence risk scoring systems for predicting AF recurrence following CA.

**Table 2** AUC and Optimal Cutoff Values of 11 AF Prognostic Scoring Systems in the Overall Cohort

Predicting Scores	AUC	95% CI	P value	Sensitivity	Specificity	Youden Index	Optimal Cutoff Value
APPLE	0.524	0.424–0.624	0.642	0.634	0.424	0.058	2
BASE-AF <sub>2</sub>	0.666	0.572–0.759	0.001	0.659	0.624	0.283	3
C <sub>2</sub> HES <sub>2</sub>	0.525	0.420–0.630	0.630	0.098	0.968	0.066	4
CAAP-AF	0.497	0.399–0.594	0.949	0.064	0.976	0.040	9
CHA <sub>2</sub> DS <sub>2</sub> -VASc	0.474	0.374–0.573	0.617	0.488	0.634	0.122	2
CHADS <sub>2</sub>	0.517	0.413–0.621	0.745	0.073	0.968	0.041	3
DR-FLASH	0.498	0.400–0.596	0.975	0.360	0.780	0.140	4
HATCH	0.517	0.415–0.619	0.745	0.098	0.960	0.058	3
MB-LATER	0.734	0.646–0.821	<0.001	0.512	0.832	0.344	4
PAT <sub>2</sub> C <sub>2</sub> H	0.540	0.433–0.646	0.446	0.341	0.768	0.109	2
SCALE-CryoAF	0.702	0.600–0.804	<0.001	0.659	0.688	0.347	7

## PSM

### Propensity Scores Matching CBA Subgroup to RFCA Subgroup

Using PSM, the CBA subgroup was matched in a 1:1 ratio with the RFCA subgroup. Nearest neighbor matching was applied with a caliper width set at 0.02. A total of 49 matched pairs were successfully obtained. No statistically significant differences were observed in baseline characteristics between the two groups ( $p > 0.05$ ) (see [Supplementary Table S3](#)).

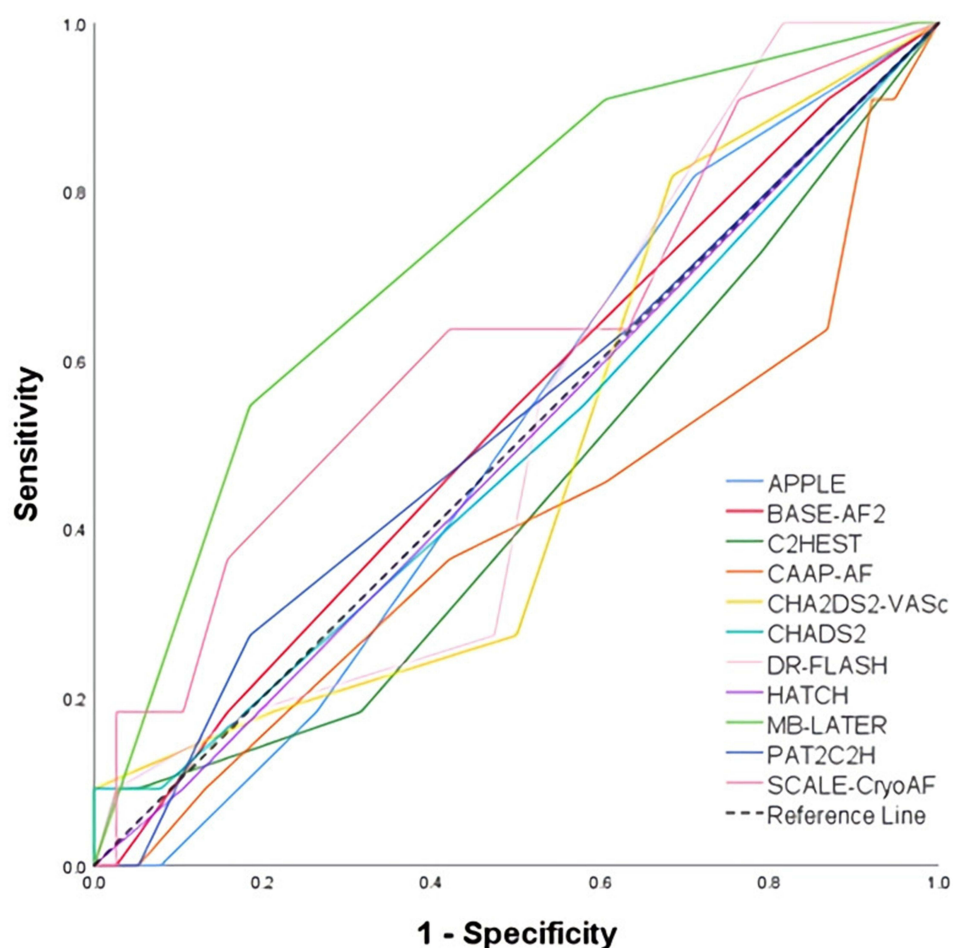
### Analysis of CBA Subgroups After PSM

In the matched subgroup of 49 patients with non-PAF who underwent PVI via CBA, participants were categorized into “no AF recurrence” and “AF recurrence” groups for comparison of recurrence risk scores. Eleven prognostic scores were calculated based on baseline clinical data. The MB-LATER score was significantly higher in the recurrence group compared to the non-recurrence group ( $p < 0.05$ ), whereas no statistically significant differences were observed for the other scores between the groups ( $p > 0.05$ ). Detailed results are presented in [Table 3](#).

ROC curves were generated for all 11 recurrence risk scores ([Figure 2](#)), and the AUC with corresponding 95% CI was calculated. Optimal cutoff values were identified using the Youden Index ([Table 4](#)). In the CBA subgroup after propensity score matching, only the MB-LATER score demonstrated significant prognostic value for AF recurrence (AUC = 0.734, 95% CI: 0.570–0.899,  $p = 0.019$ ), while the remaining 10 models did not yield statistically significant results ( $p > 0.05$ ). Calibration of the MB-LATER model was confirmed to be acceptable by the Hosmer–Lemeshow test ( $\chi^2 = 0.021$ ,  $p = 0.990$ ).

**Table 3** Comparison of AF Prognostic Scoring Systems in the CBA Subgroup After PSM. [Median, (Minimum, Maximum)]

AF Prognostic Scoring System	All	No AF Recurrence	AF Recurrence
APPLE	2 (1,5)	2 (1,3)	0.969
BASE-AF <sub>2</sub>	2.5 (1,5)	3 (1,4)	0.753
C <sub>2</sub> HES <sub>2</sub>	1 (0,4)	1 (0,4)	0.494
CAAP-AF	6 (2,10)	5 (2,8)	0.321
CHA <sub>2</sub> DS <sub>2</sub> -VASc	1.5 (0,3)	1 (0,4)	0.853
CHADS <sub>2</sub>	1 (0,2)	1 (0,3)	0.925
DR-FLASH	3 (1,6)	3 (2,6)	0.853
HATCH	1 (0,2)	1 (0,2)	0.937
MB-LATER	3 (1,4)	4 (2,4)	0.013
PAT <sub>2</sub> C <sub>2</sub> H	1 (0,3)	1 (0,2)	0.807
SCALE-CryoAF	6 (3,12)	7 (3,11)	0.214



**Figure 2** ROC curves of 11 AF recurrence risk scoring systems for predicting AF recurrence in the CBA subgroup after propensity score matching (PSM).

### Analysis of RFCA Subgroups After PSM

In the matched subgroup of 49 patients with non-PAF who underwent PVI via RFCA, participants were classified into “no AF recurrence” and “AF recurrence” groups for comparison of recurrence risk scores. Eleven prognostic scores were calculated based on baseline clinical data. The BASE-AF<sub>2</sub> score was significantly higher in the recurrence group

**Table 4** AUC and Optimal Cutoff Values of 11 AF Prognostic Scoring Systems in the CBA Subgroup After PSM

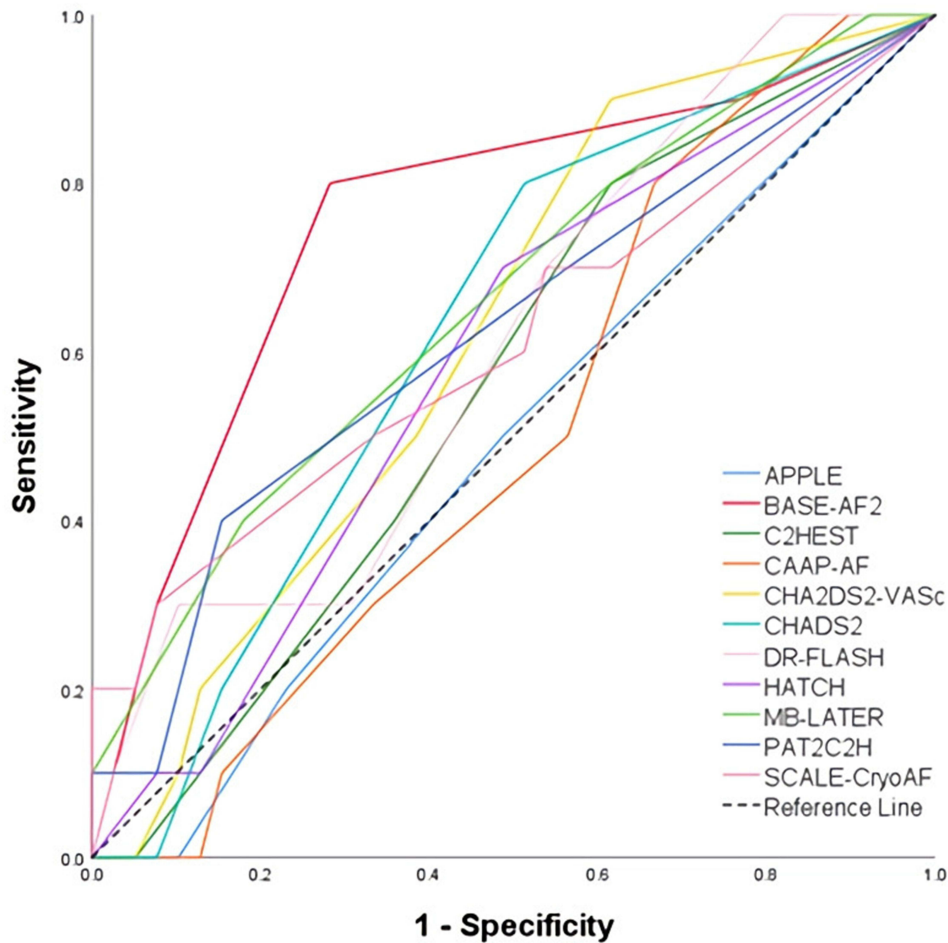
Predicting Scores	AUC	95% CI	P value	Sensitivity	Specificity	Youden Index	Optimal Cutoff Value
APPLE	0.504	0.326–0.681	0.971	0.818	0.289	0.108	2
BASE-AF <sub>2</sub>	0.530	0.338–0.722	0.765	0.545	0.500	0.045	3
C <sub>2</sub> HES <sub>T</sub>	0.437	0.242–0.631	0.525	0.316	0.818	0.134	2
CAAP-AF	0.403	0.201–0.605	0.332	0.868	0.364	0.232	5
CHA <sub>2</sub> DS <sub>2</sub> -VASc	0.482	0.294–0.670	0.857	0.500	0.727	0.227	2
CHADS <sub>2</sub>	0.492	0.292–0.692	0.933	0.579	0.455	0.033	1
DR-FLASH	0.518	0.338–0.698	0.857	1.000	0.184	0.184	2
HATCH	0.493	0.298–0.687	0.943	0.105	0.909	0.014	2
MB-LATER	0.734	0.570–0.899	0.019	0.545	0.816	0.361	4
PAT <sub>2</sub> C <sub>2</sub> H	0.523	0.323–0.722	0.820	0.273	0.816	0.089	2
SCALE-CryoAF	0.622	0.425–0.819	0.222	0.636	0.579	0.215	7

**Table 5** Comparison of AF Prognostic Scoring Systems in the RFCA Subgroup After PSM. [Median, (Minimum, Maximum)]

AF Prognostic Scoring System	All	No AF Recurrence	AF Recurrence
APPLE	1 (1,4)	1.5 (1,3)	0.913
BASE-AF <sub>2</sub>	2 (1,4)	3 (1,4)	0.011
C <sub>2</sub> HEST	1 (0,5)	1 (0,3)	0.566
CAAP-AF	6 (2,10)	5.5 (4,8)	0.951
CHA <sub>2</sub> DS <sub>2</sub> -VASc	1 (0,5)	1.5 (0,4)	0.243
CHADS <sub>2</sub>	1 (0,4)	1 (0,2)	0.233
DR-FLASH	3 (1,6)	3 (2,6)	0.285
HATCH	0 (0,3)	1 (0,3)	0.398
MB-LATER	3 (1,4)	3 (2,5)	0.122
PAT <sub>2</sub> C <sub>2</sub> H	1 (0,3)	1 (0,4)	0.243
SCALE-CryoAF	6 (3,10)	6.5 (3,11)	0.274

compared to the non-recurrence group ( $p < 0.05$ ), while no statistically significant differences were observed for the remaining scores ( $p > 0.05$ ). Further details are provided in Table 5.

ROC curves were constructed for all 11 recurrence risk scores (Figure 3), and the AUC with corresponding 95% CI was calculated. Optimal cutoff values were identified using the Youden Index (Table 6). In the RFCA subgroup after propensity



**Figure 3** ROC curves of 11 AF recurrence risk scoring systems for predicting AF recurrence in the RFCA subgroup after PSM.

**Table 6** AUC and Optimal Cutoff Values of 11 AF Prognostic Scoring Systems in the RFCA Subgroup After PSM

Predicting Scores	AUC	95% CI	P value	Sensitivity	Specificity	Youden Index	Optimal Cutoff Value
APPLE	0.487	0.294–0.681	0.901	0.103	1.000	0.103	4
BASE-AF <sub>2</sub>	0.758	0.578–0.937	0.013	0.800	0.718	0.518	3
C <sub>2</sub> HES <sub>2</sub>	0.562	0.378–0.745	0.552	0.800	0.385	0.185	1
CAAP-AF	0.506	0.328–0.685	0.951	0.800	0.333	0.133	5
CHA <sub>2</sub> DS <sub>2</sub> -VASc	0.623	0.448–0.798	0.234	0.900	0.385	0.285	1
CHADS <sub>2</sub>	0.626	0.447–0.804	0.224	0.800	0.487	0.287	1
DR-FLASH	0.613	0.426–0.799	0.275	0.300	0.897	0.197	5
HATCH	0.588	0.399–0.778	0.392	0.700	0.513	0.213	1
MB-LATER	0.660	0.468–0.853	0.121	0.400	0.821	0.221	4
PAT <sub>2</sub> C <sub>2</sub> H	0.623	0.416–0.830	0.234	0.400	0.846	0.246	2
SCALE-CryoAF	0.615	0.399–0.832	0.264	0.300	0.923	0.223	8

score matching, the BASE-AF<sub>2</sub> score demonstrated significant prognostic value for AF recurrence (AUC = 0.758, 95% CI: 0.578–0.937,  $p = 0.013$ ), whereas the other 10 models did not yield statistically significant results ( $p > 0.05$ ). Model calibration, as assessed by the Hosmer–Lemeshow test, indicated good fit for the BASE-AF<sub>2</sub> score ( $\chi^2 = 2.292$ ,  $p = 0.318$ ).

## Discussion

The European Society of Cardiology guidelines recommend that clinicians present AF treatment options to patients based on the estimated risk of recurrence. Accurate prediction of outcomes following AF ablation may assist in clinical decision-making and patient selection. According to prior studies, risk factors such as advanced age, hypertension, and heart failure were considered predictors of AF recurrence after ablation.<sup>20,21</sup> These factors contribute to the development of an arrhythmogenic substrate and structural or electrical atrial remodeling. Additional risk factors include AF type, LAD enlargement, and recurrence during the blanking period.

The recurrence of blanking period showed a high correlation with the recurrence of AF in this study. The essence of PVI is to set up an “isolation zone” between the pulmonary vein and the left atrium, and the local ablation process will inevitably lead to part of the myocardial injury, resulting in a local acute inflammatory response. Similar to wound healing, myocardial injury undergoes a physiological process of repair and scar formation. This time period is approximately 3 months, and some studies have shown a 50% incidence of recurrence in the blanking period after catheter ablation of AF,<sup>22</sup> with a multifactorial pathophysiological basis, including early recovery of pulmonary venous electrical conduction, difficult-to-improve arrhythmogenic atrial substrate, inflammation in the atria, and autonomic modulation. Approximately 60% of AF, atrial flutter, and atrial tachycardia of >30 s duration occurring during this 3-month period recover spontaneously and remain in sinus rhythm for an extended period of time. Such “recurrences” are defined in the criteria of “blanking period recurrence” or “early recurrences” and are not classified or categorized as “recurrence”. It cannot be called a “catheter ablation” failure. These three months are the “blanking period” after catheter ablation. However, a single-center study in Korea<sup>23</sup> showed that 1 in 4 patients had a recurrence during the blanking period, and about 69.6% of those who had a recurrence during the blanking period eventually had an AF recurrence. In view of the high correlation between AF recurrence during the blanking period and post-procedure recurrence, a Swedish study<sup>24</sup> proposed a new perspective on the duration of the “blanking period”, suggesting that the “blanking period” after catheter ablation should be shortened to 48 days post-procedure. In our study, similar results were obtained, with 35 (21.1%) recurrences during the blanking period after catheter ablation and 24 (58.5%) recurrences after the blanking period. A similar picture emerged in the subgroup analyses.

In this study, the BASE-AF<sub>2</sub>, MB-LATER, and SCALE-CryoAF scoring systems demonstrated favorable prognostic performance incorporating LAD, AF type, and blanking period recurrence factors, commonly associated with AF recurrence risk. Estimating recurrence risk remains a clinical challenge due to the complex interplay among various contributing factors. The prognostic models assessed in this study integrate multiple variables into a composite risk score to enhance the reliability of outcome prediction following CA.

Although the concept of comparing AF-recurrence prediction tools has been addressed in previous work, including the large-scale study by Mulder et al, our findings provide distinct and complementary insights.<sup>25</sup> Mulder et al demonstrated limited predictive performance across multiple scores in a heterogeneous AF cohort.<sup>25</sup> In contrast, the present study specifically focuses on a more homogeneous population—individuals with non-PAF undergoing PVI as a standalone procedure—and includes a broader set of 11 calculators, three of which incorporate blanking-period recurrence as a core component. Furthermore, propensity-score-matched subgroup analyses were performed based on ablation modality. While our sample size is comparatively smaller, the homogeneity of patient characteristics and procedural approach minimizes confounding and allows a more direct evaluation of score–outcome relationships. Thus, the novelty of this study lies not in repeating prior conclusions, but in clarifying context-specific modifying factors that influence score performance in a defined clinical scenario.

In this study, both the CHA<sub>2</sub>DS<sub>2</sub>-VASc and CHADS<sub>2</sub> scores, originally developed for assessing thromboembolic risk in patients with AF, demonstrated poor prognostic performance in predicting AF recurrence across the overall group and subgroup analyses. Although effective in evaluating stroke risk, these scoring systems have limited applicability for recurrence prediction. The C<sub>2</sub>HEST score, developed in Chinese populations and validated among Korean individuals for predicting new-onset AF in East Asians, is currently being investigated for its relevance in AF recurrence prediction.<sup>10</sup> The HATCH score, which shares several risk parameters with C<sub>2</sub>HEST, is used to evaluate the progression from paroxysmal to non-paroxysmal AF. The observed limited predictive value of these scores in this study may be attributable to structural and electrophysiological differences in atrial remodeling between AF subtypes.

The DR-FLASH score was developed to assess the presence of left atrial low voltage areas (LVA), serving as a predictor of outcomes following ablation. LVAs are typically defined by bipolar ECG voltage < 0.5 mV using the CARTO mapping system and are considered indicative of left atrial fibrosis. Prior studies have indicated that LVAs are more extensive during AF compared to sinus rhythm and that LVA is an independent predictor of late AF recurrence.<sup>26,27</sup> Although ablation strategies targeting LVA have been developed, their use in this study was limited. In the RFCA group, intraoperative voltage mapping was used to select patients with relatively mild atrial fibrosis for PVI alone, while the CBA group did not undergo preprocedural LVA assessment due to technical constraints. This approach resulted in a reduced prevalence of LVA in the study group, thereby diminishing the prognostic use of the DR-FLASH score.

PVI remains the foundational technique in AF CA and is widely accepted for the treatment of paroxysmal AF. However, when applied to non-PAF, the efficacy of PVI alone has been suboptimal. Current consensus proposes that along with PVI, ablation strategies should target arrhythmogenic substrates beyond the pulmonary veins through substrate modification. Common strategies include intraluminal guided approaches (eg, rotor ablation, complex fractionated atrial electrogram ablation) and anatomical approaches (eg, linear ablation). Although existing evidence suggests that combining PVI with additional substrate modification does not significantly increase the success rate compared to PVI alone, recent advances in ablation techniques and protocols may offer potential clinical benefits.<sup>28</sup>

A novel ablation strategy, the Marshall-PLAN, was proposed by French investigators. It integrates ethanol infusion into the vein of Marshall, coronary sinus ablation, PVI, and linear ablation of the left atrial apex, mitral isthmus, and tricuspid isthmus. Among 68 individuals with persistent AF treated using this strategy, an AF recurrence rate of only 21% was reported.<sup>29</sup> Furthermore, pulsed electric field ablation has emerged as a promising technique with broad applicability when compared to conventional ablation modalities.<sup>30</sup>

Two previous studies<sup>31,32</sup> proposed prediction model calculator, which were established through machine learning and another predictive model. However, these calculators were overly complex. Moreover, compared to the models included in this study, it did not significantly improve the predictive value. If a faster prediction method for atrial fibrillation recurrence after surgery could be achieved through simplifying the model, it would have higher clinical value. However, this network calculator failed to do so.

In this study, the prognostic value of multiple AF recurrence prediction models was evaluated in individuals with non-PAF undergoing PVI alone. The findings may assist clinicians in selecting prognostic assessment tools with favorable predictive performance. For patients identified as having a high risk of recurrence, adjunctive substrate modification strategies and novel ablation technologies may be considered to improve the success rate of CA. From a comprehensive

AF management perspective, along with optimizing ablation techniques, addressing modifiable upstream and downstream risk factors may contribute to more effective maintenance of sinus rhythm.

This study has several limitations. First, the research was conducted as a single-center retrospective analysis with a relatively small sample size, necessitating further validation through multicenter, large-sample, prospective cohort studies. Second, the possibility of asymptomatic AF recurrence in the post-procedural period cannot be excluded. The use of intermittent and scheduled electrocardiographic monitoring may have resulted in the discovery of asymptomatic episodes, potentially leading to an underestimation of the actual recurrence rate. Third, the three scoring systems identified as having prognostic value in this study all included recurrence during the blanking period as a risk factor, limiting their utility for preprocedural patient selection or counseling. These models can only provide comprehensive recurrence prognosis following the completion of the blanking period. Notably, none of the other scoring systems that excluded blanking period recurrence as a risk factor demonstrated satisfactory prognostic performance. Fourth, in individuals with AF recurrence, no further intracardiac electrophysiological studies were performed to determine if the recurrence was attributable to the resumption of pulmonary vein conduction, the emergence of new ectopic foci outside the pulmonary veins, or undetected foci during the initial ablation procedure. Fifth, several potential risk factors such as epicardial adipose tissue, cardiac biomarkers, atrial function, and atrial fibrosis were not incorporated into the existing prognostic models. Additionally, the potential improvement in prognostic performance through the integration of these factors into current models was not explored. Sixth, due to limitations in data availability, some prognostic models were not included in the analysis. For instance, the ATLAS model and VAT-DHF model, which requires measurement of left ventricular (LV) volume, and the LAGO model, which involves assessment of LV morphology, were excluded for reasons of data acquisition convenience.

## Conclusion

The BASE-AF<sub>2</sub>, MB-LATER, and SCALE-CryoAF scoring systems demonstrated prognostic value for AF recurrence following PVI alone. Among patients with non-PAF, the MB-LATER score was more suitable for those undergoing CBA-based PVI, whereas the BASE-AF<sub>2</sub> score was more appropriate for those receiving RFCA-based PVI. The decision to go for PVI in patients with persistent and long-term persistent AF should be based on a higher probability of success and lower rates of recurrence. However, the aforementioned predictive models rely partially on postoperative information, which imposes certain limitations on preoperative decision-making. Furthermore, they require broader external validation, which indeed constrains the predictive capabilities of these models.

## Abbreviations

PVI, Pulmonary vein isolation; AF, Atrial Fibrillation; non-PAF, Non-Paroxysmal Atrial Fibrillation; CBA, Cryo-balloon Ablation; RFCA, Radiofrequency Ablation; CTA, Computerized Tomography Angiography; TTI, Time to Isolation; ECG, Electrocardiogram; eGFR, estimated Glomerular Filtration Rate; LVEF, Left Ventricular Ejection Fractions; LAD, Left Atrial Diameter; BMI, Body Mass Index; CHD, Coronary Heart Disease; COPD, Chronic Obstructive Pulmonary Disease; HT, Hypertension; DM, Diabetes Mellitus; HF, Heart Failure; AAD, Antiarrhythmic Drugs; DM, Diabetes Mellitus; TIA, Transient Ischemic Attack; ESC, European Society of Cardiology; LVA, Low Voltage Areas.

## Data Sharing Statement

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

## Ethics Approval and Consent to Participate

This study was conducted with approval from the Ethics Committee of Fujian Medical University Union Hospital (Approval Number: 2023KY113). This study was conducted in accordance with the declaration of Helsinki. Written informed consent was obtained from all participants.

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## Disclosure

The authors declare that they have no conflict of interests.

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