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PREDICTORS OF ATRIAL TACHYARRHYTHMIAS INDUCIBILITY AFTER PULMONARY VEIN ISOLATION IN PATIENTS WITH PAROXYSMAL ATRIAL FIBRILLATION

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Aim. To identify predictors of atrial tachyarrhythmias inducibility after pulmonary vein isolation in patients with paroxysmal atrial fibrillation (AF).

Methods. The study included 82 patients (63.65±9.21 years, 45 men (54.9%)) with paroxysmal AF referred for primary radiofrequency ablation. All patients underwent voltage mapping of the left atrium, with areas exhibiting bipolar signal amplitudes less than 0.5 mV identified as low-voltage areas (LVA). After pulmonary vein isolation, arrhythmia induction was performed by pacing with a cycle length of 180 milliseconds sequentially from the left atrial appendage, anterior wall, roof, posterior wall, and mitral isthmus area. When sustained tachycardia was induced, electrophysiological mapping of the left atrium was performed to verify the tachycardia mechanism.

Results. Tachyarrhythmias were not induced in 25 patients (30.48%), while 57 patients experienced induced tachyarrhythmias of varying durations (69.52%). The arrhythmia mechanisms in patients with induced sustained tachycardias were macro re-entry in 12 cases (38.7%), atrial fibrillation in 12 cases (38.7%), and a combination of macro re-entry and atrial fibrillation in 7 cases (22.6%). We found a statistically significant correlation between the induction of any type of arrhythmia and body mass index ($p=0.014$) and left atrial volume ($p=0.024$). A correlation was also found between AF induction and left atrial volume ($p=0.016$) and the percentage of LVA ($p=0.014$). The threshold value of the percentage of LVA indicating the probability of AF induction was 2.2%. No correlation was found between macro re-entry induction and any of the investigated factors.

Conclusions. Independent predictors of sustained arrhythmia induction were left atrial volume and body mass index. Atrial fibrillation induction was associated with left atrial volume and LVA percentage with a threshold of $\geq 2.2\%$. No significant associations with the investigated parameters were found for macro re-entry.

Key words: atrial fibrillation; radiofrequency ablation; pulmonary vein isolation; atrial fibrillation induction; left atrial low voltage

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Atrial fibrillation (AF) is the most common tachyarrhythmia in clinical practice and is associated with an increased risk of stroke, heart failure, and overall mortality [1]. Among available treatment options, radiofrequency ablation (RFA) with pulmonary vein isolation (PVI) remains one of the most effective strategies in patients with paroxysmal AF, targeting arrhythmogenic triggers originating from the pulmonary vein (PV) ostia [2]. However, the efficacy of this procedure remains suboptimal. According to various studies, AF recurrence occurs in 25-40% of patients, highlighting the need to identify reliable predictors of procedural success [3-5]. One of the approaches used to assess the risk of AF recurrence after PVI is arrhythmia induction using different pacing protocols. The clinical significance and prognostic value of inducibility remain

controversial: some studies have reported an association with an increased risk of recurrence, whereas others have demonstrated no significant relationship [6-9].

Several studies have suggested that AF inducibility after PVI is associated with specific clinical and electrophysiological characteristics of the atria. In a prospective study by Leong-Sit et al. (2013), age and arterial hypertension were independent predictors of inducible sustained arrhythmias [9]. In a study by Satomi et al. (2008), inducibility of atrial tachyarrhythmias was associated with a smaller area of isolation around the pulmonary veins [8]. At the same time, the role of other important clinical factors, such as comorbidities, sex, and the size and extent of low-voltage areas (LVA) in the left atrium (LA), remains insufficiently investigated.

A number of studies have demonstrated an association between AF inducibility and atrial low-voltage areas [7, 10, 11]. However, these studies have several limitations, including insufficient voltage mapping density and inclusion of heterogeneous populations combining patients with paroxysmal and persistent AF.

Given the clinical relevance of this issue and the limited available data, the aim of the present study was to identify predictors of atrial tachyarrhythmia inducibility following PVI in patients with paroxysmal AF.

MATERIALS AND METHODS

The study included 82 patients with paroxysmal AF referred for primary RFA. The mean age was 63.65 ± 9.21 years; 45 patients were men (54.9%) and 37 were women (45.1%). In all patients, arrhythmia was clinically significant and manifested as episodes of palpitations and/or reduced exercise tolerance. AF was documented in all patients by electrocardiography (ECG) or 24-hour ECG monitoring. No other atrial arrhythmias were recorded. The duration of arrhythmia history ranged from 2 months to 16 years (mean duration 77.43 months).

RFA was performed under general endotracheal anaesthesia. Antiarrhythmic drugs, except beta-blockers, were discontinued 5 days prior to the procedure; amiodarone was discontinued at least 3 weeks before the procedure. Left atrial voltage maps were constructed using the CARTO 3 electroanatomical mapping system (Biosense Webster, USA) during pacing from the proximal electrode pair of a diagnostic catheter positioned in the coronary sinus

with a cycle length of 600 ms. Mapping was performed using a multielectrode PentaRay catheter (Biosense Webster, USA) with the “tissue proximity” feature, ensuring a distance of mapping points from the anatomical atrial model of no more than 5 mm. The Confidense module was used with the following parameters: catheter position stability 6 mm, local activation time stability (for sinus rhythm mapping) 6 ms, and electroanatomical point density 1 mm [12].

All voltage maps consisted of at least 1500 electrogram points, with a mean of 1885 ± 121 points. Following mapping, voltage maps were analysed to identify LVA and calculate their proportion. Areas with bipolar signal amplitude <0.5 mV were defined as LVA [12, 13]. For each map, the percentage of LVA (LVA%) was calculated. LA volume was calculated based on the reconstructed anatomical model, including the left atrial appendage but excluding the pulmonary veins.

PVI was performed using a contact force-sensing ablation catheter (Thermocool SmartTouch, Biosense Webster, USA) with a point-by-point technique, guided by the VisiTag SurPoint (Ablation Index) module, with lesion size of 3 mm and interlesion distance not exceeding 3 mm. Ablation parameters included power settings of 50 W for the anterior left atrial wall and 40 W for the posterior wall. Ablation Index targets were 470–490 for the anterior wall and 420–430 for the posterior wall.

PVI was verified using a 20-pole diagnostic Lasso catheter (Biosense Webster, USA) positioned in the pulmonary veins. After achieving electrical isolation, pacing was performed in each pulmonary vein; in the presence of conduction, additional radiofrequency applications were delivered until complete bidirectional block was achieved.

Following confirmation of isolation of all pulmonary veins, arrhythmia induction was performed using rapid pacing of the left atrium from the distal electrode pair of the SmartTouch ablation catheter (Biosense Webster, USA) with a cycle length of 180 ms for 5 seconds or until tachycardia induction. Stimulation was performed sequentially from the left atrial appendage, anterior wall, roof, posterior wall, and mitral isthmus region. In cases of sustained tachycardia induction, electrophysiological mapping of the left atrium was performed to determine the arrhythmia mechanism.

A tachyarrhythmia with organized atrial activity and a cycle length ≥ 200 ms was classified as atrial flutter (AFL). In cases of sustained AFL, activation mapping of the left atrium was performed, and entrainment pacing was used to confirm macrore-entry localization. In cases of AF induction, electrophysiological mapping of the left atrium was performed with electrogram analysis. After identification of the arrhythmia mechanism, addi-

Clinical and echocardiographic characteristics of patients with inducible and non-inducible arrhythmias

Parameter	Arrhythmia not induced	Arrhythmia induced	p
Age, years	63.72 ± 7.79	63.61 ± 9.83	0.962
Male, n	13	32	0.729
Female, n	12	25	
DAH, months	56.0 [24.0; 135.0]	48.0 [18.0; 72.0]	0.191
Diabetes mellitus, n	0	7	0.095
CAD, n	5	15	0.591
GFR, ml/min/1.73 m ²	65.73 ± 15.48	68.26 ± 16.38	0.529
BMI, kg/m ²	28.04 ± 5.50	30.26 ± 5.07	0.079
CHA ₂ DS ₂ -VASC, points	2 [2; 3]	3 [2; 3]	0.218
IVS thickness, mm	12 [10.0; 12.0]	11 [10.0; 12.7]	0.771
LVPW thickness, mm	11 [10.0; 12.0]	11 [10.0; 12.0]	1.0
LA AP diameter, cm	4.0 [4.0; 4.0]	4.0 [4.0; 4.0]	0.224
LA volume, mL	65.65 ± 18.14	67.75 ± 20.12	0.687
LAA emptying velocity, cm/s	64.0 [50.5; 79.5]	60.0 [47.5; 67.0]	0.164
LVEF, %	62 [59.0; 67.0]	60.5 [8.0; 62.0]	0.12
LVA <0.5 mV, %	1.3 [0.00; 3.50]	1.0 [0.00; 4.50]	0.736

Note: here and throughout DAH - duration of arrhythmia history; CAD - coronary artery disease; GFR - glomerular filtration rate; BMI - body mass index; IVS - interventricular septum; LVPW - left ventricular posterior wall; LV - left ventricle; AP - anteroposterior; LA - left atrium; LAA - left atrial appendage; EF - ejection fraction; LVA - low-voltage areas.

Table 1.

tional ablation was performed until restoration of sinus rhythm. If arrhythmia persisted despite ablation, electrical cardioversion was performed. Following linear ablation, conduction block was verified after restoration of sinus rhythm.

Correlation analysis was performed to assess associations between AF inducibility and arrhythmia duration, comorbidities (left ventricular hypertrophy, coronary artery atherosclerosis, diabetes mellitus), body mass index (BMI), glomerular filtration rate, anteroposterior left atrial diameter (measured by echocardiography), left ventricular ejection fraction, left atrial appendage emptying velocity (assessed by preoperative transoesophageal echocardiography), left atrial volume (derived from the electroanatomical map), left atrial volume index, and LVA%.

Statistical analysis was performed using StatTech v. 4.8.7 (StatTech LLC, Russia). Quantitative variables were assessed for normality using the Shapiro-Wilk test (for sample size <50) or the Kolmogorov-Smirnov test (for sample size ≥50). Normally distributed variables were presented as mean (M) and standard deviation (SD), with 95% confidence intervals (95% CI). Non-normally distrib-

uted data were presented as median (Me) with interquartile range [Q1-Q3]. Categorical variables were expressed as absolute numbers and percentages.

Comparisons between two groups with normally distributed variables and equal variances were performed using Student's t-test. For non-normally distributed variables, the Mann-Whitney U test was used. Categorical variables were compared using Pearson's chi-square test (when expected frequencies >10) or Fisher's exact test (when expected frequencies <10). Odds ratios (OR) with 95% CI were calculated as a measure of effect size. The strength of association between categorical variables was assessed using Cramer's V, interpreted according to Rea and Parker (2014). Receiver operating characteristic (ROC) curve analysis was used to assess the discriminative ability of quantitative predictors, with optimal cut-off values determined using the Youden index. A p-value <0.05 was considered statistically significant.

RESULTS

Tachyarrhythmias were not inducible in 25 patients (30.5%), whereas 57 patients (69.5%) demonstrated induc-

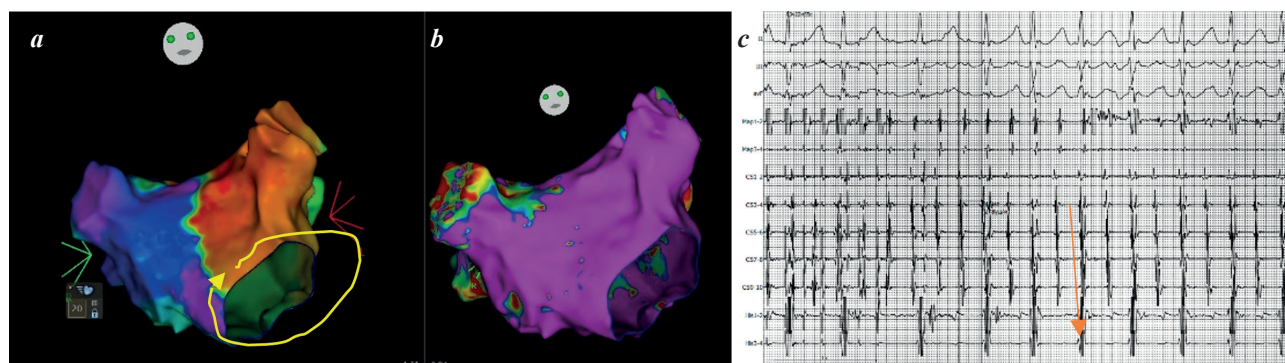


Figure 1. Activation (a) and voltage (b) mapping of the left atrium in a patient with induced perimitral atrial flutter (cycle length 237 ms), the moment of arrhythmia induction and activation sequence recorded on the coronary sinus catheter (c). Here and throughout: CS1-2 and CS9-10 denote the distal and proximal electrode pairs of the coronary sinus catheter; the arrow indicates propagation of activation along the coronary sinus catheter from early to late activation. On the activation map, red indicates early activation and purple indicates late activation; the arrow shows propagation from early to late activation. On the voltage map, purple indicates areas with voltage >0.5 mV, red indicates areas with voltage <0.1 mV, and green and orange indicate areas with voltage between 0.1 and 0.5 mV.

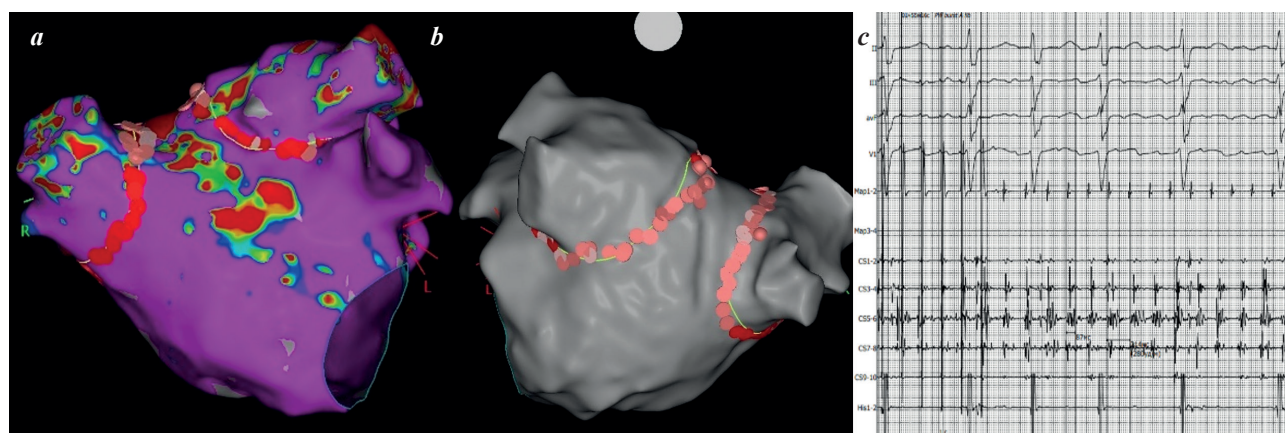


Figure 2. Voltage mapping (a), ablation lesion set design (b), and intracardiac electrograms at the moment of AF induction (c). On the voltage map, red points correspond to an ablation index >460, and pink points to an ablation index of 400-460. Electrograms show the moment of AF induction following pacing from the mapping catheter positioned in the left atrial appendage (cycle length 180 ms). On CS electrode pairs 5-6 and 7-8, continuous fractionated activity is observed (duration 87 ms, cycle length 214 ms). The mapping catheter is positioned in the left atrial appendage.

Table 2.

Analysis of factors associated with arrhythmia inducibility at different duration thresholds

	Any arrhythmia			Atrial fibrillation			Macro re-entry		
	30 seconds	1 minute	2 minutes	30 seconds	1 minute	2 minutes	30 seconds	1 minute	2 minutes
Age	p=0.969 AUC=0.501	p=0.948 AUC=0.511	p=0.493 AUC=0.548	p=0.598 AUC=0.504	p=0.598 AUC=0.537	p=0.722 AUC=0.506	p=0.774 AUC=0.522	p=0.452 AUC=0.566	p=0.393 AUC=0.576
Sex	p=0.926 V=0.01	p=0.842 V=0.02	p=0.727 V=0.04	p=1.000 V=0.03	p=1.000 V=0.01	p=1.000 V=0.03	p=0.852 V=0.02	p=0.612 V=0.08	p=0.443 V=0.09
DAH	p=0.933 AUC=0.505	p=0.648 AUC=0.530	p=0.201 AUC=0.588	p=0.552 AUC=0.515	p=0.552 AUC=0.546	p=0.237 AUC=0.572	p=0.975 (AUC=0.502)	p=0.992 (AUC=0.501)	p=0.387 AUC=0.566
Diabetes mellitus	p=0.038 V=0.27	p=0.013 V=0.26	p=0.200 V=0.17	p=0.038 V=0.24	p=0.038 V=0.26	p=0.306 V=0.09	p=0.394 V=0.1	p=0.365 V=0.12	p=0.660 V=0.04
CAD	p=1.000 V=0.03	p=0.602 V=0.07	p=1.000 V=0.02	p=0.358 V=0.09	p=0.358 V=0.11	p=1.000 V=0.06	p=0.408 V=0.1	p=0.572 V=0.07	p=1.000 V=0.04
GFR	p=0.751 AUC=0.521	p=0.906 AUC=0.513	p=0.320 AUC=0.561	p=0.329 AUC=0.535	p=0.329 AUC=0.562	p=0.595 AUC=0.553	p=0.706 AUC=0.522	p=0.811 AUC=0.505	p=0.840 AUC=0.501
BMI	p=0.013 AUC=0.661	p=0.014 AUC=0.661	p=0.042 AUC=0.640	p=0.136 AUC=0.595	p=0.136 AUC=0.599	p=0.293 AUC=0.624	p=0.115 AUC=0.612	p=0.123 AUC=0.613	p=0.155 AUC=0.608
IVS thickness	p=0.715 AUC=0.524	p=0.611 AUC=0.534	p=0.527 AUC=0.545	p=0.976 AUC=0.516	p=0.976 AUC=0.502	p=0.795 AUC=0.509	p=0.256 AUC=0.584	p=0.271 AUC=0.585	p=0.233 AUC=0.596
LA AP diameter	p=0.087 AUC=0.628	p=0.049 AUC=0.645	p=0.037 AUC=0.645	p=0.116 AUC=0.597	p=0.116 AUC=0.629	p=0.136 AUC=0.620	p=0.12 AUC=0.601	p=0.123 AUC=0.610	p=0.131 AUC=0.593
LA emptying velocity	p=0.096 AUC=0.610	p=0.083 AUC=0.616	p=0.099 AUC=0.616	p=0.698 AUC=0.506	p=0.488 AUC=0.531	p=0.862 AUC=0.556	p=0.125 AUC=0.611	p=0.230 AUC=0.589	p=0.188 AUC=0.601
LA volume (EAM)	p=0.033 AUC=0.638	p=0.024 AUC=0.648	p=0.053 AUC=0.634	p=0.016 AUC=0.650	p=0.016 AUC=0.686	p=0.028 AUC=0.660	p=0.101 AUC=0.619	p=0.160 AUC=0.607	p=0.118 AUC=0.617
Indexed LA volume (EAM)	p=0.263 AUC=0.573	p=0.258 AUC=0.574	p=0.213 AUC=0.586	p=0.499 AUC=0.551	p=0.258 AUC=0.588	p=0.440 AUC=0.561	p=0.377 AUC=0.563	p=0.629 AUC=0.536	p=0.478 AUC=0.554
LVA %	p=0.154 AUC=0.590	p=0.101 AUC=0.605	p=0.641 AUC=0.531	p=0.014 AUC=0.657	p=0.014 AUC=0.685	p=0.170 AUC=0.658	p=0.878 AUC=0.511	p=0.926 AUC=0.507	p=0.713 AUC=0.527

Note: AUC (area under the curve) - area under the curve; V - Cramér's V coefficient.

ible tachyarrhythmias of varying duration. Patients with and without inducible arrhythmias did not differ significantly in baseline clinical and echocardiographic characteristics (Table 1).

Among patients with sustained inducible tachycardias, the arrhythmia mechanisms were macrore-entry in 12 cases (38.7%), atrial fibrillation (AF) in 12 cases (38.7%), and a combination of macrore-entry and AF in 7 cases (22.6%). Thus, macrore-entry was verified as the arrhythmia mechanism in 19 patients, and AF in 19 patients. Among macrore-entry tachyarrhythmias, perimitral atrial flutter (AFL) was induced in 10 patients, roof-dependent AFL in 2 patients, and dual-loop (perimitral and roof-dependent) AFL in 7 patients (Fig. 1, 2).

A statistically significant association was identified between several clinical and morphofunctional parameters and inducibility of any tachyarrhythmia (Table 2). BMI was associated with arrhythmia inducibility across all duration thresholds. LA volume, measured from the electroanatomical map, was associated with inducibility at thresholds of 30 seconds and 1 minute, whereas anteroposterior LA diameter (assessed by echocardiography) was associated at thresholds of 1 and 2 minutes. The presence of diabetes mellitus was also associated with inducibility of arrhythmias lasting more than 30 seconds and 1 minute; however, the strength of this association was weak (Cramer's V 0.24 for 30 seconds and 0.26 for 1 minute). The most consistent and robust predictors of inducibility were BMI and LA volume.

Analysis of AF-specific inducibility demonstrated similar patterns: LVA% was associated with AF inducibility at thresholds of 30 seconds and 1 minute, whereas LA volume showed a significant association across all evaluated durations (Table 2). Diabetes mellitus again showed a weak association (Cramer's V 0.24). Overall, an inducibility threshold of 1 minute provided the most consistent and reproducible associations for both AF and any induced tachyarrhythmia.

The discriminative ability of LVA% for predicting AF inducibility was assessed using ROC analysis for three arrhythmia duration thresholds (Fig. 3). The area under the curve (AUC) values were 0.657 for 30 seconds, 0.685 for 1 minute, and 0.658 for 2 minutes, with the highest discriminative performance observed at the 1-minute threshold.

Further analysis of sensitivity and specificity using the Youden index identified an optimal LVA% cut-off value of 2.2% (Fig. 4). At LVA% $\geq 2.2\%$, AF inducibility was predicted with the highest accuracy. The sensitivity and specificity of the model were 66.7% and 70.3%, respectively. The positive predictive value was 38.7%, and the negative predictive value was 88.2%.

No statistically significant associations were found between macrore-entry inducibility and any of the investigated parameters (Table 2). In all patients with sustained inducible arrhythmias, the minimum distance between the left and right pulmonary vein antral isolation lines at the left atrial roof was additionally measured. In patients with confirmed roof-dependent or dual-loop AFL, this distance did not differ from that observed in patients without inducible arrhythmia of this type ($p=0.591$).

DISCUSSION

Several studies and meta-analyses have demonstrated a significantly increased risk of AF recurrence in patients with inducible arrhythmias following pulmonary vein isolation (PVI) [14]. Despite variations in induction protocols, AF inducibility has been proposed both as a procedural endpoint for radiofrequency ablation and as an independent predictor of postoperative AF recurrence [15].

However, data on predictors of AF inducibility remain inconsistent. In the study by Leong-Sit et al. (2013), age and arterial hypertension were associated with AF inducibility [9]. In contrast, Santangeli et al. (2018) and Darma et al. (2020) did not identify significant predictors of arrhythmia inducibility [15-17]. Notably, in the studies by Leong-Sit et al. and Santangeli et al., AF induction was performed after PVI combined with ablation of non-pulmonary vein triggers identified during isoproterenol infusion [9, 16]. Such an approach results in heterogeneity of the ablation strategy across patients and, in our view, limits the reliability of identifying predictors of AF inducibility. In addition, the study by Darma et al. included both paroxysmal and persistent AF, which likely introduced further heterogeneity and influenced the results [17].

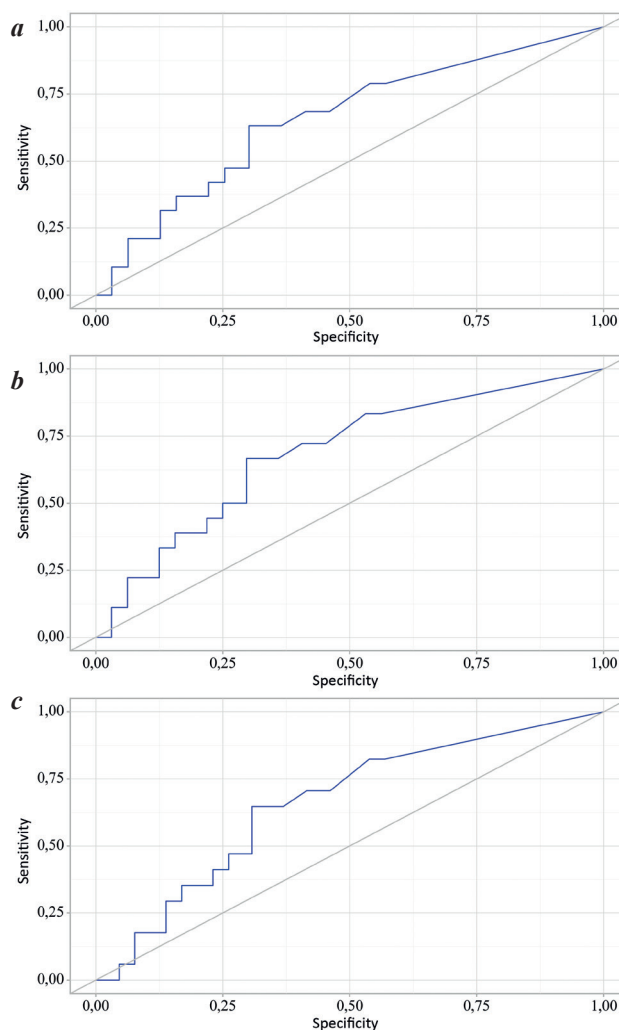


Figure 3. ROC curves demonstrating the discriminative performance of LVA% for predicting AF inducibility at AF durations of 30 seconds (a), 1 minute (b), and 2 minutes (c).

An important factor influencing outcomes is the definition of sustained versus non-sustained arrhythmia. In studies of AF induction using transoesophageal pacing, episodes lasting more than 15 seconds have been shown to have diagnostic relevance [18]. However, in those studies, induction was performed in native atria rather than after PVI.

In a meta-analysis by Liu et al. (2020), an induced arrhythmia duration ≥ 1 minute was associated with a significant relationship between non-inducibility and reduced recurrence risk [19]. This is consistent with meta-regression data indicating that shorter inducibility thresholds may be associated with greater predictive value [14]. In our study, a threshold of 1 minute demonstrated the strongest and most consistent associations with clinical and electrophysiological parameters for both AF induction and inducibility of any arrhythmia, supporting its clinical relevance.

In our cohort, predictors of sustained arrhythmia inducibility included LA volume and BMI, while AF-specific inducibility was additionally associated with LVA%. The threshold for defining low-voltage areas remains a matter of debate; in our study, a cut-off of <0.5 mV was used, as it is the most widely accepted threshold in clinical studies and is supported by the 2024 EHRA/HRS/APHRS/LAHS Expert Consensus Statement [12]. In our analysis, the median LVA% at the <0.5 mV threshold was 1.25%, whereas at an alternative threshold of 0.1 mV it was only 0.01%. Given the minimal representation of LVA at 0.1 mV and the widespread use of the <0.5 mV threshold in the literature, all primary analyses were performed using this threshold.

AF inducibility and left atrial volume

LA size, measured using different modalities, is an established predictor of adverse outcomes in the general population. In the Framingham Heart Study, LA diameter was a significant predictor of stroke and mortality in individuals over 50 years of age without comorbidities [20]. Enlargement of the LA has also been associated with an increased risk of AF recurrence after PVI [21].

In our study, increased LA volume was identified as a predictor of sustained arrhythmia inducibility after PVI, consistent with previous findings. Johner et al. (2019) demonstrated that, in repeat procedures following initial PVI, patients with inducible arrhythmias had significantly larger LA volumes (86.7 ± 25.3 vs. 72.0 ± 28.9 mL; $p=0.001$), whereas pulmonary vein reconnection was not

associated with this parameter [22]. It can be hypothesized that LA volume reflects the degree of structural remodeling (atrial dilation, conduction heterogeneity, and conduction slowing), which facilitates maintenance of arrhythmia following rapid pacing.

In our study, a correlation was also observed with anteroposterior LA diameter; however, the association with LA volume derived from electroanatomical mapping was stronger. This likely reflects the higher accuracy of volumetric assessment using electroanatomical mapping compared with echocardiography. Importantly, indexed LA volume was not a predictor of arrhythmia inducibility after PVI. This may suggest that the contribution of LA volume is modest; however, it should not be disregarded, as it demonstrated associations with AF inducibility across all durations and with arrhythmia inducibility at thresholds of 30 seconds and 1 minute.

AF inducibility and body mass index

A large body of evidence has consistently shown that increased BMI is an independent risk factor for AF. For example, a meta-analysis including 51 studies and 626,603 patients demonstrated that each 5-unit increase in BMI was associated with a 10-29% increase in the risk of AF [23]. Tsang et al. (2008) also showed an association between increasing BMI and progression of AF from the paroxysmal to the persistent form [24].

Animal models have demonstrated that obesity induces structural and electrophysiological changes in the myocardium, including LA enlargement, atrial fibrosis confirmed histologically, reduced conduction velocity, and increased conduction heterogeneity [25]. The same study also reported increased AF inducibility associated with obesity. Conversely, reduction in BMI has been associated with improvement in AF course. In the LEGACY study, sustained long-term weight loss was associated with a significant reduction in AF burden and maintenance of sinus rhythm [26].

Some investigators have suggested that the effect of increased BMI on AF may be mediated by LA dilatation [27]. However, in our study, increased BMI was an independent predictor of AF inducibility, as BMI did not correlate with LVA ($p=0.853$) and showed only a significant but moderate correlation with LA volume ($p=0.003$, $r=0.310$). This indirectly supports the existence of a metabolic pathway of LA remodeling, including inflammation and fatty infiltration, which is not necessarily associated with voltage reduction. In addition, based on findings from previous studies, a BMI <27 kg/m² has been recommended in patients with AF to reduce disease burden [28]. This is consistent with our findings, in which the discriminative threshold was 27.7 kg/m².

AF inducibility and left atrial low-voltage areas

An interesting finding was that patients in whom AF was identified as the arrhythmia mechanism had a higher LVA%. Only a limited number of studies have investigated the relationship between arrhythmia inducibility and LVA. In the previously mentioned study by Chang et al. (2007), the presence of atrial low-voltage areas was associated with AF inducibility after PVI [7]. However, that study used left and right atrial maps consisting of only 233 ± 24 and 228 ± 69 points, respectively, which may have substan-

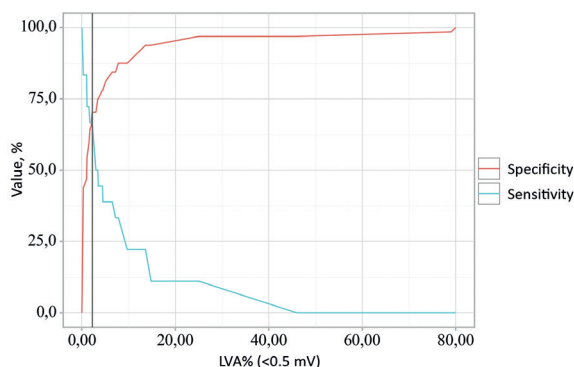


Figure 4. Sensitivity and specificity analysis of the model across different probability threshold values for AF inducibility.

tially influenced estimation of LVA% and the final results. In contrast, analysis based on high-density mapping with more than 1500 electrograms, as used in our study, did not reveal an association between LVA% and inducibility of any arrhythmia, but did demonstrate a correlation with AF inducibility.

Other studies reporting an association between atrial LVA and AF inducibility included patients with both paroxysmal and persistent AF [10, 29]. In our study, only patients with paroxysmal AF were included, and they had lower LVA%.

In the study by Kawai et al. (2019), which investigated non-pulmonary vein triggers of AF, voltage at trigger sites during sinus rhythm mapping was 0.3 ± 0.16 mV [29]. Several studies have also demonstrated improved outcomes of radiofrequency ablation for AF when additional ablation of complex fractionated electrograms and LVA was performed in selected patient groups [31, 32].

In the vast majority of studies, including ours, the conventional threshold of <0.5 mV has been used to define LVA. However, Yagishita et al. (2017) showed that the presence of areas with voltage <1.1 mV in patients without LVA <0.5 mV was an independent predictor of AF recurrence after PVI [33]. This observation highlights the need for further investigation to determine the optimal threshold distinguishing preserved from low-voltage LA myocardium.

Importantly, according to our findings, the predictive performance of LVA% remained moderate (AUC=0.685), and the optimal cut-off value was 2.2%, only slightly above zero. In addition, model sensitivity at this threshold was relatively low (66.7%), which limits its utility as a stand-alone diagnostic tool. In our view, this may be explained by several factors.

First, arrhythmogenesis is multifactorial. AF induction depends not only on the presence of fibrosis, but also on LA anatomy, inflammatory and metabolic processes, age, BMI, and other factors [34].

Second, voltage mapping has methodological limitations. It remains an indirect method, and the threshold of <0.5 mV may lead to overestimation or underestimation of the true extent of fibrosis, depending on the mapping platform and filter settings used [35].

Third, threshold effects and heterogeneity may play a role. Several studies suggest that the probability of AF recurrence or inducibility increases only after a certain threshold is exceeded. For example, in the study by Vlachos et al. (2002), LVA% $>10\%$ of the total atrial surface area was the only significant predictor of arrhythmia recur-

rence after the procedure [36]. In our cohort, most patients had lower values (mean LVA% 5.08%, median 1.15%), which may have reduced the overall discriminative ability.

Finally, LVA represent an important but not exclusive mechanism of AF formation. Arrhythmogenic substrates may also be located in regions of preserved voltage [37].

Differences between atrial fibrillation and atrial flutter

According to our data, patients with induced AF demonstrated higher LVA%, whereas patients with induced AFL were characterised by significantly lower LVA%. Experimental studies have shown that sustained induced AFL does not lead to structural changes in the atrial myocardium, whereas induced AF is associated with structural remodelling, including atrial fibrosis [38]. Based on this, it can be hypothesised that if a proportion of a patient's arrhythmia burden consists of AFL, this may be associated with a lower LVA% in the LA.

An additional noteworthy finding is the high proportion of AFL among induced arrhythmias, which is consistent with published data. It has been reported that, following PVI in patients with paroxysmal AF, inducible atrial tachycardias occur in 16-19% of cases and are frequently based on a macro re-entry mechanism [38].

Furthermore, the occurrence of AFL in the late period after PVI has been widely described. In large observational registries, organised atrial tachycardias, including typical and atypical AFL, are observed in 8-9% of patients [40]. Other studies report that organised left atrial tachycardias after PVI occur less frequently, in approximately 2.9% of patients, but may account for up to 15% of all arrhythmia recurrences following AF ablation [41]. After cryoballoon PVI, the incidence of late AFL is comparable, at approximately 7.7% [42].

These findings support the concept that the occurrence of AFL after PVI is an expected phenomenon and reflects the formation or activation of a macro re-entry substrate.

CONCLUSION

Independent predictors of sustained arrhythmia inducibility in our study were LA volume and BMI. AF inducibility was associated with LA volume and LVA%, with a threshold of $\geq 2.2\%$. No significant associations were identified between macro re-entry arrhythmias and the studied parameters. Age, sex, duration of arrhythmia history, and most comorbidities were not associated with arrhythmia inducibility after PVI.

REFERENCES

1. Chugh SS, Havmoeller R, Narayanan K, et al. World-wide epidemiology of atrial fibrillation. *Circulation*. 2014;129(8): 837-47. <https://doi.org/10.1161/circulationaha.113.005119>.
2. Haïssaguerre M, Jaïs P, Shah DC, et al. Spontaneous initiation of atrial fibrillation by ectopic beats originating in the pulmonary veins. *N Engl J Med*. 1998;339(10): 659-66. <https://doi.org/10.1056/nejm199809033391003>.
3. Jaïs P, Cauchemez B, Macle L, et al. Catheter ablation versus antiarrhythmic drugs for atrial fibrillation: the A4 study. *Circulation*. 2008;118(24): 2498-505. <https://doi.org/10.1161/circulationaha.108.772582>.
4. Weerasooriya R, Khairy P, Litalien J, et al. Catheter ablation for atrial fibrillation: are results maintained at 5 years of follow-up? *J Am Coll Cardiol*. 2011;57(2): 160-6. <https://doi.org/10.1016/j.jacc.2010.05.061>.
5. Calkins H, Reynolds MR, Spector P, et al. Treatment of atrial fibrillation with antiarrhythmic drugs or radiofrequency ablation: two systematic literature reviews and meta-analyses. *Circ Arrhythm Electrophysiol*. 2009;2: 349-61. <https://doi.org/10.1161/CIRCEP.108.824789>.
6. Haïssaguerre M, Sanders P, Hocini M, et al. Changes

- in atrial fibrillation cycle length and inducibility during catheter ablation and their relation to outcome. *Circulation*. 2004;109: 3007-13. <https://doi.org/10.1161/01.cir.0000130645.95357.97>.
7. Chang SL, Tai CT, Lin YJ, et al. The efficacy of inducibility and circumferential ablation with pulmonary vein isolation in patients with paroxysmal atrial fibrillation. *J Cardiovasc Electrophysiol*. 2007;18: 607-11. <https://doi.org/10.1111/j.1540-8167.2007.00823.x>.
 8. Satomi K, Tilz R, Takatsuki S, et al. Inducibility of atrial tachyarrhythmias after circumferential pulmonary vein isolation in patients with paroxysmal atrial fibrillation: clinical predictor and outcome during follow-up. *Europace*. 2008;10(8): 949-54. <https://doi.org/10.1093/europace/eun131>.
 9. Leong-Sit P, Robinson M, Zado ES, et al. Inducibility of atrial fibrillation and flutter following pulmonary vein ablation. *J Cardiovasc Electrophysiol*. 2013;24(6): 617-23. <https://doi.org/10.1111/jce.12088>.
 10. Sonoda K, Fukushima T, Takei A, et al. Association between left atrial low-voltage area and induction and recurrence of macroreentrant atrial tachycardia in pulmonary vein isolation for atrial fibrillation. *J Interv Card Electrophysiol*. 2024;67(5): 1199-210. <https://doi.org/10.1007/s10840-024-01760-8>.
 11. Kawai S, Nagaoka K, Takase S, et al. Presence of low voltage area predicts atrial tachyarrhythmia inducibility with atrial burst pacing after pulmonary vein isolation. *Eur Heart J*. 2020;41: ehaa946.0595. <https://doi.org/10.1093/ehjci/ehaa946.0595>.
 12. Tcivkovskii VYu, Chapurnykh AV, Nizhnichenko VB. Left atrial voltage characteristics in patients with persistent atrial fibrillation. *Journal of Arrhythmology*. 2025;32(3): 5-13. (In Russ.) <https://doi.org/10.35336/VA-1468>.
 13. Tzeis S, Gerstenfeld EP, Kalman J, et al. 2024 European Heart Rhythm Association/Heart Rhythm Society/Asia Pacific Heart Rhythm Society/Latin American Heart Rhythm Society expert consensus statement on catheter and surgical ablation of atrial fibrillation. *Europace*. 2024 Mar 30;26(4): Corrected and republished in: *Heart Rhythm*. 2024 Sep;21(9): e31-e149. <https://doi.org/10.1093/europace/euae043>.
 14. Millenaar D, Becker N, Pavlicek V, et al. Inducibility of atrial fibrillation after catheter ablation predicts recurrences: a meta-analysis. *Pacing Clin Electrophysiol*. 2021;44(4): 667-76. <https://doi.org/10.1111/pace.14216>.
 15. Richter B, Gwechenberger M, Filzmoser P, et al. Is inducibility of atrial fibrillation after radio frequency ablation really a relevant prognostic factor? *Eur Heart J*. 2006;27: 2553-9. <https://doi.org/10.1093/eurheartj/ehl307>.
 16. Santangeli P, Zado ES, Garcia FC, et al. Lack of prognostic value of atrial arrhythmia inducibility after catheter ablation. *Heart Rhythm*. 2018;15(5): 660-5. <http://doi.org/10.1016/j.hrthm.2017.10.023>.
 17. Darma A, Daneschnejad SS, Gaspar T, et al. Role of inducibility and its dynamic change in the outcome of catheter ablation of atrial fibrillation: a single center prospective study. *J Cardiovasc Electrophysiol*. 2020;31(3): 705-11. <https://doi.org/10.1111/jce.14355>.
 18. Chapurnykh AV, Ovechkin AO, Tarlovskaya EI, et al. Diagnostic significance of atrial fibrillation induced by ultra-frequent atrial electrostimulation in patients with coronary artery disease and/or essential hypertension. *Journal of Arrhythmology*. 1999;(12): 35-8. (In Russ.)
 19. Liu H, Yuan P, Zhu X, et al. Is atrial fibrillation non-inducibility by burst pacing after ablation associated with reduced recurrence? A systematic review and meta-analysis. *J Am Heart Assoc*. 2020;9(14): e015260. <https://doi.org/10.1161/jaha.119.015260>.
 20. Pritchett AM, Jacobsen SJ, Mahoney DW, et al. Left atrial volume as an index of size: a population-based study. *J Am Coll Cardiol*. 2003;41: 1036-43. [http://doi.org/10.1016/S0735-1097\(02\)02981-9](http://doi.org/10.1016/S0735-1097(02)02981-9).
 21. Berruezo A, Tamborero D, Mont L, et al. Pre-procedural predictors of atrial fibrillation recurrence after circumferential pulmonary vein ablation. *Eur Heart J*. 2007;28: 836-41. <https://doi.org/10.1093/eurheartj/ehm027>.
 22. Johner N, Shah DC, Giannakopoulos G, et al. Volition of post-pulmonary vein isolation atrial fibrillation inducibility at redo ablation: Electrophysiological evidence of extra-pulmonary vein substrate progression. *Heart Rhythm*. 2019;16(8): 1160-6. <https://doi.org/10.1016/j.hrthm.2019.02.026>.
 23. Wong CX, Sullivan T, Sun MT, et al. Obesity and the Risk of Incident, Post-Operative, and Post-Ablation Atrial Fibrillation: A Meta-Analysis of 626,603 Individuals in 51 Studies. *JACC Clin Electrophysiol*. 2015;1(3): 139-52. <https://doi.org/10.1016/j.jacep.2015.04.004>.
 24. Tsang TS, Barnes ME, Miyasaka Y, et al. Obesity as a risk factor for the progression of paroxysmal to permanent atrial fibrillation: a longitudinal cohort study of 21 years. *Eur Heart J*. 2008;29(18): 2227-33. <https://doi.org/10.1093/eurheartj/ehn324>.
 25. Abed HS, Samuel CS, Lau DH, et al. Obesity results in progressive atrial structural and electrical remodeling: implications for atrial fibrillation. *Heart Rhythm*. 2013 Jan;10(1): 90-100. <https://doi.org/10.1016/j.hrthm.2012.08.043>.
 26. Pathak RK, Middeldorp ME, Meredith M, et al. Long-Term Effect of Goal-Directed Weight Management in an Atrial Fibrillation Cohort: A Long-Term Follow-Up Study (LEGACY). *J Am Coll Cardiol*. 2015;65(20): 2159-69. <https://doi.org/10.1016/j.jacc.2015.03.002>.
 27. Wang TJ, Parise H, Levy D, et al. Obesity and the risk of new-onset Atrial Fibrillation. *JAMA*. 2004;292(20): 2471-7. <https://doi.org/10.1542/aer.2018.76.2>.
 28. Al-Kaisey AM, Kalman JM. Obesity and Atrial Fibrillation: Epidemiology, Pathogenesis and Effect of Weight Loss. *Arrhythm Electrophysiol Rev*. 2021;10(3): 159-64. <https://doi.org/10.15420/aer.2021.36>.
 29. Masuda M, Fujita M, Iida O, et al. Influence of underlying substrate on atrial tachyarrhythmias after pulmonary vein isolation. *Heart Rhythm*. 2016;13(4): 870-8. <https://doi.org/10.1016/j.hrthm.2015.12.029>.
 30. Kawai S, Mukai Y, Inoue S, et al. Non-Pulmonary Vein Triggers of Atrial Fibrillation Are Likely to Arise from Low-Voltage Areas in the Left Atrium. *Sci Rep*. 2019;9(1): 1-11. <https://doi.org/10.1038/s41598-019-48669-1>.
 31. Rolf S, Kircher S, Arya A, et al. Tailored atrial substrate modification based on low-voltage areas in catheter ablation of atrial fibrillation. *Circ Arrhythm Electrophysiol*. 2014;7: 825-33. <https://doi.org/10.1161/>

circep.113.001251.

32. Wu SH, Jiang WF, Gu J, et al. Benefits and risks of additional ablation of complex fractionated atrial electrograms for patients with atrial fibrillation: a systematic review and meta-analysis. *Int J Cardiol.* 2013;169: 35-43. <https://doi.org/10.1016/j.ijcard.2013.08.083>.
33. Yagishita A, Sparano D, Cakulev I, et al. Identification and electrophysiological characterization of early left atrial structural remodeling as a predictor for atrial fibrillation recurrence after pulmonary vein isolation. *J Cardiovasc Electrophysiol.* 2017;28(6): 642-50. <https://doi.org/10.1136/heartjnl-2018-314267>.
34. Wijesurendra RS, Casadei B. Mechanisms of atrial fibrillation. *Heart.* 2019;105(24): 1860-1867. <https://doi.org/10.1136/heartjnl-2018-314267>.
35. Yagishita A, DE Oliveira S, Cakulev I, et al. Correlation of Left Atrial Voltage Distribution Between Sinus Rhythm and Atrial Fibrillation: Identifying Structural Remodeling by 3-D Electroanatomic Mapping Irrespective of the Rhythm. *J Cardiovasc Electrophysiol.* 2016 Aug;27(8): 905-12. <https://doi.org/10.1111/jce.13002>.
36. Vlachos K, Efremidis M, Letsas KP, et al. A. Low-voltage areas detected by high-density electroanatomical mapping predict recurrence after ablation for paroxysmal atrial fibrillation. *J Cardiovasc Electrophysiol.* 2017 Dec;28(12): 1393-1402. <https://doi.org/10.1111/jce.13321>.
37. Huang T, Chen J, Müller-Edenborn B, et al. Validating left atrial fractionation and low-voltage substrate during atrial fibrillation and sinus rhythm-A high-density mapping study in persistent atrial fibrillation. *Front Cardiovasc Med.* 2022 Oct 18;9: 1000027.
38. Guichard JB, Naud P, Xiong F, et al. Comparison of Atrial Remodeling Caused by Sustained Atrial Flutter Versus Atrial Fibrillation. *J Am Coll Cardiol.* 2020;76(4): 374-88. <https://doi.org/10.1016/j.jacc.2020.05.062>.
39. Satomi K, Tilz R, Takatsuki S, et al. Inducibility of atrial tachyarrhythmias after circumferential pulmonary vein isolation in patients with paroxysmal atrial fibrillation: clinical predictor and outcome during follow-up. *Europace.* 2008 Aug;10(8): 949-54. <https://doi.org/10.1093/europace/eun131>.
40. Akerström F, Bastani H, Insulander P, et al. Comparison of regular atrial tachycardia incidence after circumferential radiofrequency versus cryoballoon pulmonary vein isolation in real-life practice. *J Cardiovasc Electrophysiol.* 2014 Sep;25(9): 948-952. <https://doi.org/10.1111/jce.12423>.
41. Gerstenfeld EP, Callans DJ, Dixit S, et al. Mechanisms of organized left atrial tachycardias occurring after pulmonary vein isolation. *Circulation.* 2004 Sep 14;110(11): 1351-7. <https://doi.org/10.1161/01.CIR.0000141369.50476.D3>.
42. Baman JR, Kaplan RM, Diaz CL, et al. Characterization of atrial flutter after pulmonary vein isolation by cryoballoon ablation. *J Interv Card Electrophysiol.* 2020 Mar;57(2): 233-240. <https://doi.org/10.1007/s10840-019-00560-9>.

