

Diagnostic Accuracy of 12-Lead Electrocardiographic Algorithms in Predicting the Origin of Idiopathic Premature Ventricular Complexes: Comparison with Ablation Outcomes

● Selim Ekinci, ● Hakan Gökalep Uzun

University of Health Sciences Türkiye, İzmir City Hospital, Clinic of Cardiology, İzmir, Türkiye

ABSTRACT

Introduction: Accurate preprocedural localization of the origin of idiopathic premature ventricular complexes (PVCs) using the 12-lead electrocardiogram (ECG) may facilitate procedural planning for catheter ablation. However, the diagnostic performance of ECG criteria and localization algorithms remains variable. We aimed to evaluate the diagnostic accuracy of five ECG-based criteria or algorithms in predicting the successful ablation site in idiopathic PVCs.

Methods: This study included 32 patients who underwent successful catheter ablation for idiopathic PVCs. The successful ablation site served as the reference standard. Intraprocedural ECG recordings were analyzed to calculate the ratio of S-wave amplitude in lead V2 to R-wave amplitude in lead V3 (V2S/V3R) index, V2 transition ratio, and R-wave duration index (RwDI) and to apply two previously published regional localization algorithms. For binary algorithms, diagnostic performance metrics were calculated; for regional algorithms, exact regional concordance was assessed.

Results: Among the outflow tract discrimination tools, the V2S/V3R Index showed the best performance, with 80.8% accuracy, 85.7% sensitivity, and 75.0% specificity. The V2 Transition Ratio showed modest performance, whereas the RwDI had low sensitivity (16.7%) but perfect specificity (100.0%) for identifying aortic cusp origins. For comprehensive localization, the Yamada algorithm achieved 87.5% accuracy for left-vs.-right ventricular outflow tract (LVOT-RVOT) lateralization and 81.3% exact regional concordance, while the Enriquez algorithm achieved 56.3% accuracy and 31.3% exact regional concordance, respectively. Exact regional performance was significantly better with Yamada ($p=0.0004$).

Conclusion: ECG algorithms showed variable performance for predicting the successful ablation site. The V2S/V3R index was the most useful for discriminating RVOT from LVOT, whereas the Yamada algorithm showed the best overall performance for whole-heart localization. These hypothesis-generating findings warrant external validation in larger, multicenter cohorts before clinical adoption.

Keywords: Premature ventricular contractions, catheter ablation, electrocardiography, arrhythmia localization

Introduction

Premature ventricular contractions (PVCs) observed in patients without structural heart disease are defined as idiopathic PVCs. In the presence of PVCs, the main indications for treatment are symptoms and impaired cardiac function. While beta-blockers, calcium channel blockers, certain class IC antiarrhythmic agents, and rarely amiodarone constitute the medical treatment options, catheter ablation is superior to antiarrhythmic therapy because of its low complication rates and relatively high success expectation (1,2). Compared with right ventricular outflow tract (RVOT) PVCs and left fascicular PVCs, idiopathic PVCs arising from other sites are less well studied and are generally associated with

lower ablation success rates and higher complication rates, particularly when originating from the aortic cusps, summit, or left ventricular outflow tract (LVOT). Therefore, in addition to the patient's symptoms and findings of cardiac dysfunction, the predicted PVC origin should also be taken into consideration when deciding on ablation therapy (1). The ability to predict the probable localization can, on the one hand, provide information during decision-making for the procedure and during the patient's informed consent process, and on the other hand, guide procedural planning (3). To date, many parameters and algorithms have been studied to predict the origin of PVCs from the 12-lead ECG. While some of these aims to predict RVOT/LVOT differentiation, others aim to predict the precise location of the PVCs (3-10).



Address for Correspondence: Selim Ekinci, MD, University of Health Sciences Türkiye, İzmir City Hospital, Clinic of Cardiology, İzmir, Türkiye

E-mail: mdsekinci@gmail.com **ORCID ID:** orcid.org/0000-0001-6168-0298

Cite this article as: Ekinci S, Uzun HG. Diagnostic accuracy of 12-lead electrocardiographic algorithms in predicting the origin of idiopathic premature ventricular complexes: comparison with ablation outcomes. *İstanbul Med J*. 2026; 27(4): 325-334

Received: 06.05.2026

Accepted: 12.08.2026

Publication Date: 30.10.2026



©Copyright 2026 by the University of Health Sciences Türkiye, İstanbul Training and Research Hospital/İstanbul Medical Journal published by Galenos Publishing House. Licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 (CC BY-NC-ND) International License

We aimed to evaluate the ability of five ECG algorithms to predict the successful ablation site using preprocedural surface ECG morphology in patients who underwent catheter ablation for idiopathic PVCs and in whom the successful ablation site was definitively identified. The ratio of S-wave amplitude in lead V2 to R-wave amplitude in lead V3 (V2S/V3R) index and the V2 transition ratio were primarily assessed for RVOT-LVOT discrimination, the R-wave duration index (RwDI) for differentiating aortic sinus cusps (ASC) from RVOT origins, and the algorithms proposed by Enriquez et al. (10) and Yamada et al. (3) for predicting all possible anatomical localizations.

Methods

Study Population

This single-center retrospective accuracy study included 32 patients who underwent successful catheter ablation of idiopathic PVCs at İzmir City Hospital, Department of Cardiology between June 2025 and February 2026. The data analyzed in the study were derived from intracardiac electrograms, 12-lead ECG recordings, and three-dimensional activation maps obtained during the procedure; all were recorded and stored using the EnSite X EP System (Abbott, Abbott Park, IL, USA), which is routinely used at İzmir City Hospital. Clinical and demographic data were obtained from the hospital information management system records. Patients were included in the study if they had an evaluable 12-lead ECG recording of the clinical PVC before ablation, if the clinical PVC could be mapped during the electrophysiological study, and if the successful ablation site could be definitively identified from the procedural records. Patients with structural heart disease, baseline bundle branch block, ventricular-paced rhythm, or conduction abnormalities that could interfere with ECG interpretation and those in whom adequate mapping could not be performed because of insufficient PVC frequency or limited anatomical access were excluded. For the purposes of this study, the term “idiopathic PVCs” was operationally defined as focal, monomorphic PVCs whose 12-lead electrocardiogram (ECG) morphology was consistent with an origin in anatomically defined idiopathic foci (outflow tracts, aortic cusps, aortomitral continuity, papillary muscles, fascicles, annular regions, or the cardiac crux), in the absence of ECG, echocardiographic, or imaging evidence of a scar-related arrhythmogenic substrate. Patients with a history of coronary artery disease were not excluded a priori; however, patients with prior myocardial infarction, regional wall-motion abnormalities consistent with an arrhythmogenic scar, or PVC morphology suggesting a scar-related origin were excluded. Reductions in left ventricular ejection fraction in this cohort were considered consistent with PVC-induced cardiomyopathy rather than primary structural heart disease, given the focal PVC morphology and the absence of a defined ischemic or non-ischemic substrate.

Clinical Characteristics, Symptoms, and Comorbidities

The patients' demographic (age, sex, diabetes, hypertension, chronic obstructive pulmonary disease, coronary artery disease, smoking), clinical (presence of palpitations, irregular heartbeat, or syncope), and echocardiographic (LV end-diastolic/end-systolic diameters, left atrial diameter, and LV ejection fraction) data were collected from the hospital information management system records.

Ablation Procedure

Catheter ablation of PVCs is routinely performed using the EnSite™ X EP System (Abbott, Abbott Park, IL, USA). According to the ECG findings and operator preference, mapping is initially undertaken from either the right or the left ventricle. When the earliest activation site cannot be identified or effective ablation cannot be achieved from the initial chamber, mapping is continued from the contralateral ventricle. Activation mapping and, when necessary, pace mapping are performed using a TactiCath™ Contact Force Ablation Catheter, Sensor Enabled™ (Abbott), and radiofrequency energy is delivered at the site of earliest activation of the clinical PVC. Radiofrequency energy was delivered in power-controlled mode at a power of 35 W (20 W in the coronary venous system), with a target contact force of 10-20 g and irrigation at 17mL/min. If aortic cusp or LV summit origins were suspected, selective coronary angiography was performed to delineate the proximity of the coronary arteries. Acute procedural success defined as abolition of the targeted PVC with no spontaneous or inducible ($\pm$ isoproterenol) recurrence during a 30 minute observation period.

Electrocardiographic Assessment

A PVC was identified as an ectopic ventricular beat occurring earlier than expected, displaying widened QRS complexes (>120 ms) and QRS/T-wave morphologies that differed from those of sinus beats. ECG data, such as PVC QRS duration, coupling interval, and post-PVC interval type (compensatory, non-compensatory, or interpolated) were obtained from the patients' 12-lead ECGs during the procedure. PVC burden (the percentage of heartbeats that are PVCs over a specified monitoring period), mean heart rate, and presence of ventricular tachycardia were obtained from ambulatory ECG recordings and hospital information management system recordings. ECG time intervals, QRS durations, and amplitudes were manually measured using the integrated digital caliper tools of the EnSite™ X EP System, enabling precise ECG waveform annotation and interval calculation.

First, all parameters to be used in the algorithms were analyzed and entered into the data collection form. For this purpose, the following were recorded for each PVC: the bundle branch block pattern in lead V1, frontal axis, lead I polarity, QRS patterns in aVL, aVR, and V6, presence of positive concordance, QRS voltage in the inferior leads, precordial transition location during sinus rhythm and during PVC, and QRS durations and amplitudes in leads V1, V2, and V3. The maximum deflection index (MDI) was calculated as the shortest time from QRS onset to the maximum deflection in any precordial lead divided by the total QRS duration.

To minimize observer bias, all 12-lead ECG measurements and algorithmic classifications were independently performed by two reviewers blinded to the successful ablation site, intraprocedural three dimensional mapping data, and ablation outcome. The ECG analyses were completed and recorded before the reviewers had access to procedural data.

ECG Algorithms and Indices Evaluated in the Study

The parameters obtained from the 12-lead surface ECG were used to predict the localization according to 5 different indices or algorithms.

1. The V2S/V3R index: The V2S/V3R index was calculated by dividing the S-wave amplitude in lead V2 by the R-wave amplitude in lead V3 measured during a clinical PVCs or ventricular tachycardia. A value of 1.5 or lower was considered suggestive of an origin in the LVOT. This index was applied only to cases showing left bundle branch block (LBBB) morphology with an inferior axis (4).

2. The V2 transition ratio was assessed in patients with LBBB morphology, an inferior axis, and precordial transition at lead V3. For this calculation, the R-wave proportion in lead V2 during ventricular arrhythmia was compared with that during sinus rhythm. Origins were then classified according to the previously defined threshold for this criterion (6). For this index, only PVCs/VTs with an LBBB morphology, an inferior axis, and a transition in V3 were included in the analysis.

3. RwdI was evaluated in the appropriate outflow tract subgroup. The index was obtained by measuring the longer R-wave duration between leads V1 and V2 and expressing it as a percentage of the total QRS duration of the PVC. In addition, the R/S amplitude index was determined using the largest R/S amplitude ratio in leads V1 or V2. This criterion was used to differentiate ASC origins from RVOT origins in patients with LBBB morphology and inferior axis (9). For this index, only PVCs/VTs with an LBBB morphology and an inferior axis were included in the analysis.

4. Four step algorithm proposed by Enriquez et al. (10): The four-step algorithm described by Enriquez et al. (10) was applied to classify the likely site of origin. In this algorithm, ventricular arrhythmias are initially categorized into broad anatomical regions using frontal plane axis and lead I polarity. Localization is further refined by incorporating precordial transition, QRS duration, V1 morphology, and aVL/aVR patterns. This method enables assessment of both outflow tract and non-outflow tract regions, including the aortic cusps, aortomitral continuity, atrioventricular annuli, papillary muscles, para-Hisian region, and cardiac crux (10).

5. The algorithm proposed by Yamada et al. (3), the Yamada localization approach, was used as a comprehensive ECG framework for whole-heart PVC localization. This approach integrates multiple ECG features, including bundle branch block pattern, frontal axis, lead V6 polarity, precordial transition, QRS duration, MDI, and region-specific QRS morphologies. It was used to assign probable origins across a wide range of anatomical sites, including the outflow tracts, aortic sinuses, aortomitral continuity, left ventricular summit, mitral and tricuspid annuli, papillary muscles, fascicular regions, moderator band, and other right ventricular muscular structures (3).

Follow-Up and Recurrence Assessment

Follow-up data were obtained retrospectively from the hospital information management system. Recurrence was defined as either documentation on surface ECG of PVCs with a morphology consistent with the ablated clinical PVC, or a PVC burden greater than 5% on ambulatory Holter monitoring during follow-up. Because follow-up was based on available clinical records rather than a prespecified prospective follow-up protocol, recurrence data should be interpreted as representing clinically documented recurrence.

Statistical Analysis

All statistical analyses were conducted using standard computational libraries in Python. Continuous variables are presented as medians (minimum-maximum), and categorical variables are expressed as absolute frequencies and percentages. The diagnostic performance of each surface ECG algorithm was evaluated against the electrophysiology-confirmed site of origin, which served as the gold standard.

For algorithms designed to differentiate systemic left-sided from right-sided origins (V2S/V3R index, V2 Transition Ratio, and RwdI), predictive utility was quantified using overall accuracy, sensitivity, specificity, positive predictive value (PPV), and negative predictive value (NPV). For algorithms predicting precise regional sub-structures [Yamada et al. (3) and Enriquez et al. (10)], performance was reported as the overall regional concordance rate.

To evaluate differences in diagnostic accuracy between algorithms tested on the same patient cohort, paired comparisons of correct classification rates were performed using the exact McNemar test. When comparing the binary differentiating algorithms, McNemar's test was restricted to the overlapping subsets of patients for whom both algorithms in each pairing were clinically applicable. A two-tailed p value of less than 0.05 was considered to indicate statistical significance. Ninety-five percent confidence intervals for all proportions (accuracy, sensitivity, specificity, and predictive values) were calculated using the Wilson score method. Cohen's kappa coefficient was calculated to assess chance-corrected agreement between each algorithm and the electrophysiology-confirmed reference standard.

To address potential selection bias from algorithm-specific applicability criteria, we performed a complete-case sensitivity analysis limited to patients in whom all three binary ECG indices were applicable. In this overlapping subset, each algorithm was classified as correct or incorrect according to its predefined diagnostic target, and paired comparisons were performed using the exact McNemar test.

Ethics Approval

The study complied with the Declaration of Helsinki and received approval from the İzmir City Hospital Institutional Review Board (decision number: 2025/522, date: 16.10.2025). Due to the retrospective nature of the study, informed consent was not obtained from the patients.

Results

A total of 32 patients underwent successful catheter ablation for symptomatic PVCs. Baseline demographic, clinical, and ECG characteristics of the cohort are summarized in Table 1. The study flow, algorithm applicability, and summary diagnostic performance are presented in Figure 1. The electrophysiology-confirmed sites of origin encompassed a diverse range of systemic left- and right-sided structures, with the definitive anatomical distribution presented in Table 2 and Figure 2. Notably, a significant proportion of the targeted arrhythmias originated from complex anatomical border zones, including the left ventricular summit, the aortic coronary cusps, and the posterior RVOT. With the ground-truth locations definitively established

by successful ablation, we evaluated the diagnostic accuracy and predictive performance of the five surface ECG algorithms. No major procedural complications (cardiac tamponade, coronary arterial injury, atrioventricular block, thromboembolism, or vascular complications requiring intervention) occurred.

During follow-up, recurrence was observed in 10 patients (33.3%). Recurrence was identified either by surface ECG documentation of PVCs

with a morphology consistent with the ablated PVC or by a PVC burden greater than 5% on follow-up Holter monitoring.

Algorithm Performance Metrics

The V2S/V3R Index

The method uses ECG indices specifically designed to differentiate left- vs. right-ventricular outflow tract origins in patients presenting with LBBB-morphology PVCs. Accordingly, 6 patients with an RBBB PVC morphology were excluded from this step, leaving a cohort of 26 patients for evaluation.

The V2 Transition Ratio

This index uses specific surface ECG criteria (such as V2 transition ratio and R-wave characteristics) to predict the site of origin, particularly to differentiate left from right outflow tracts. Based on the dataset, 11 patients were excluded from this analysis due to the absence of a V3 R/S transition.

R-wave Duration Index

This method utilizes R-wave indices in the precordial leads, such as R-wave duration and R/S amplitude ratios, to differentiate arrhythmias originating in the ASC from those arising in the RVOT.

Because of the algorithm’s highly specific anatomical focus, 14 patients were deemed not applicable to this algorithm, as their arrhythmias originated from regions outside the classical RVOT/ASC dichotomy (e.g., Summit, Papillary muscles) or exhibited an RBBB morphology, leaving an applicable cohort of 18 patients.

Performance of Outflow Tract Differentiating Algorithms

When evaluating the algorithms designed primarily to differentiate systemic left-sided from systemic right-sided origins, the V2S/V3R Index achieved the highest diagnostic utility, yielding an overall accuracy of 80.8% (21 of 26 applicable patients). It demonstrated a sensitivity of 85.7% and a specificity of 75.0% for left-sided origins, with a PPV of 80.0% and a NPV of 81.8%. The V2 transition ratio and RwDI yielded lower overall diagnostic accuracies of 61.9% (13 of 21 patients) and 72.2% (13 of 18 patients), respectively. The V2 transition ratio algorithm demonstrated a sensitivity of 61.5% and a specificity of 62.5% for left-sided targets. The RwDI exhibited low sensitivity (16.7%) but perfect specificity (100.0%) for aortic cusp origins (PPV 100.0%, NPV 70.6%).

To rigorously evaluate the relative performance of these differentiating models, pairwise exact McNemar tests were performed on the strictly overlapping patient subsets in which both algorithms in each pair were clinically applicable. Despite the observed absolute differences in overall accuracy, pairwise comparisons of their correct classification rates did not reach statistical significance for V2S/V3R index vs. V2 transition ratio (p=0.289, n=21), V2S/V3R index vs. RwDI (p=1.000, n=18), or V2 transition ratio vs. RwDI (p=1.000, n=14). These non-significant pairwise comparisons must be interpreted cautiously. Because both the overall sample and the strictly overlapping applicable subsets were small (n=14-21), the McNemar tests were markedly underpowered; therefore, the absence of a statistically significant difference does not

Table 1. Baseline demographic and clinical characteristics

Variable	Total (n=32)
Demographics	
Age (years)	54 (23-82)
Women (%)	13 (40.6%)
Comorbidities	
Diabetes	4 (12.5%)
Chronic obstructive pulmonary disease	1 (3.1%)
Coronary artery disease	4 (12.5%)
Hypertension	7 (21.9%)
Smoking	5 (15.6%)
Symptom	
Palpitation	15 (46.9%)
Skipped beats	6 (18.8%)
Syncope	3 (9.4%)
Asymptomatic	8 (25%)
Echocardiography	
LVEF (%)	55 (25-60)
LVEDD (mm)	51 (40-68)
LVESD (mm)	37 (22-60)
Left atrium diameter (mm)	35 (27-53)
Post-PVC interval	
Compensatory	28 (87.5%)
Non-compensatory	2 (6.25%)
Interpolated	2 (6.25%)
PVC QRS pattern	
LBBB	26 (81.3%)
RBBB	6 (18.8%)
PVC burden on Holter ECG	
Percent	16 (6-50)
Beats	17000 (5000-40000)
PVC QRS duration (ms)	137 (119-184)
Ablation procedure metrics	
Procedure duration (min)	73 (38-180)
Fluoroscopy time (seconds)	340 (62-890)
Number of RF applications	6 (3-17)
Cumulative RF time (seconds)	480 (120-950)
Recurrence	10/30* (33.3%)

*Two patients were lost to follow-up; recurrence percentages are calculated using the available cohort (n=30). Continuous variables are reported as median (minimum-maximum); categorical variables as n (%). LVEF: Left ventricular ejection fraction, LVEDD: Left ventricular end-diastolic diameter, LVESD: Left ventricular end-systolic diameter, PVC: Premature ventricular complex, LBBB: Left bundle branch block, RBBB: Right bundle branch block, ECG: Electrocardiogram, RF: Radiofrequency ablation

constitute evidence of equivalent diagnostic performance (i.e., absence of evidence is not evidence of absence). No formal equivalence or non-inferiority testing was undertaken, and the observed absolute

differences in accuracy should be regarded as exploratory. The diagnostic performance metrics of the V2S/V3R index, the V2 transition ratio, and the RwDI are summarized in Table 3.

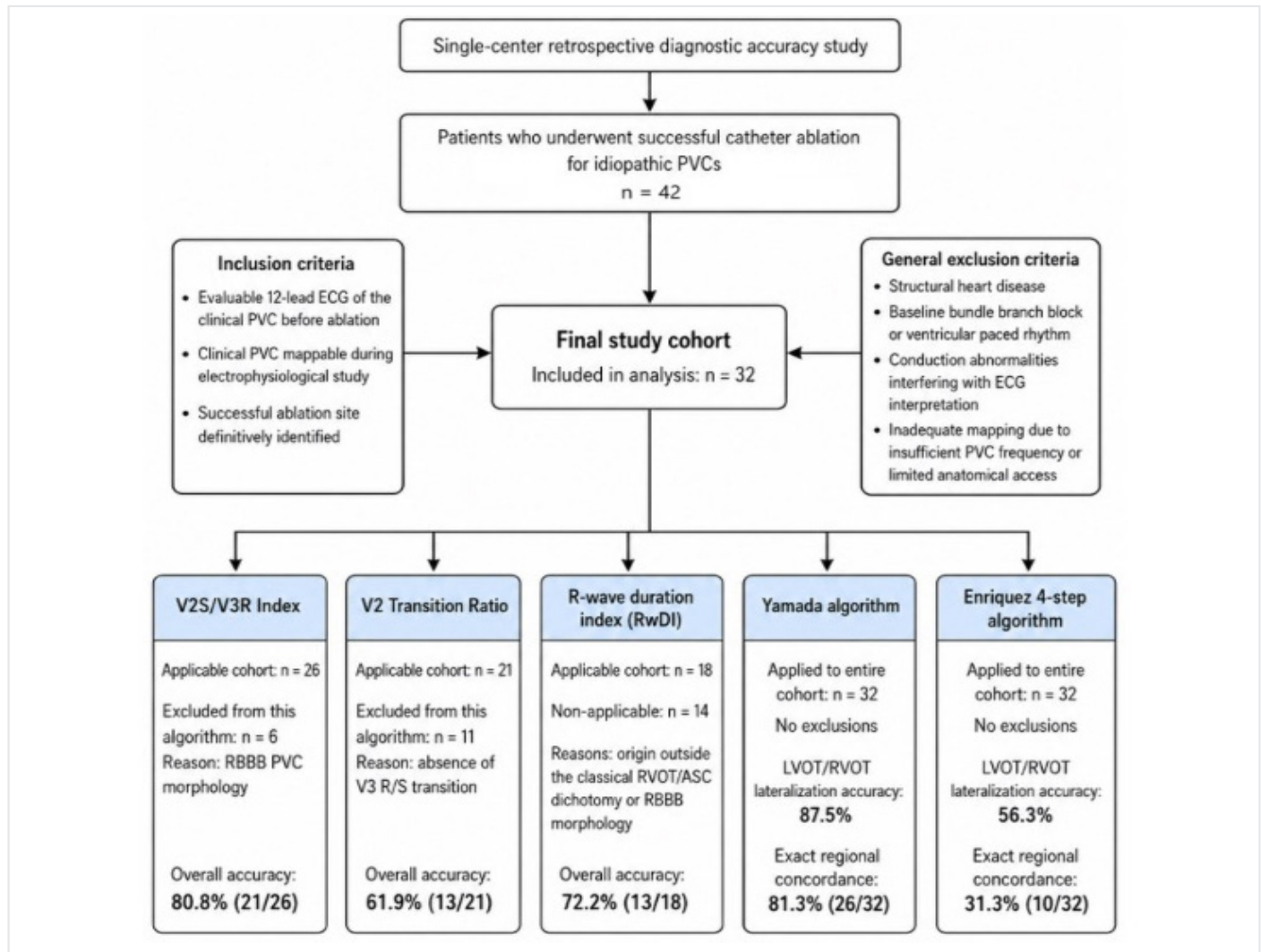


Figure 1. Study flow diagram. The flowchart summarizes the single-center, retrospective, diagnostic-accuracy design; patient eligibility; inclusion and exclusion criteria; final study cohort; algorithm-specific applicable cohorts, and summary diagnostic performance metrics. PVC: Premature ventricular complex, ECG: Electrocardiogram, V2S/V3R: Ratio of S-wave amplitude in lead V2 to R-wave amplitude in lead V3, RBBB: Right bundle branch block, RVOT: Right ventricular outflow tract, ASC: Aortic sinus cusp, LVOT: Left ventricular outflow tract, RVOT: Right ventricular outflow tract

Table 2. Anatomical distribution of successful ablation sites

Ablation side	Successful ablation location	Total
LVOT	Summit	8 (25%)
LVOT	L-RCC commissure	5 (15.6%)
LVOT	Left coronary cusp	2 (6.3%)
LVOT	Aortomitral continuity	1 (3.1%)
RVOT	Anterior RVOT	6 (18.8%)
RVOT	Posterior RVOT	5 (15.6%)
Right ventricle (other)	Parahisian	1 (3.1%)
Left ventricle (other)	Top of mitral valve	2 (6.3%)
Left ventricle (other)	Left posterior fascicle	1 (3.1%)
Left ventricle (other)	Posteromedial papillary muscle	1 (3.1%)

LVOT: Left ventricular outflow tract, RVOT: Right ventricular outflow tract

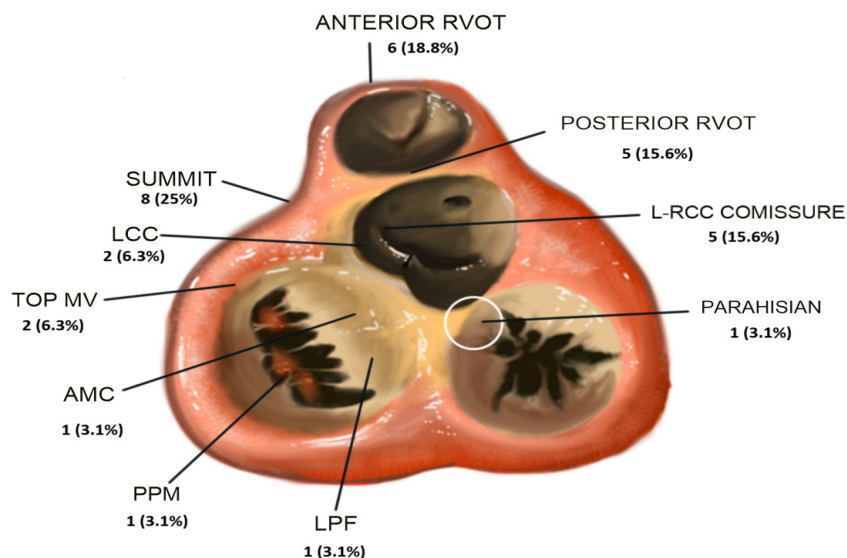


Figure 2. Anatomical distribution of electrophysiologically confirmed premature ventricular complex origins. The schematic illustrates the successful ablation sites in the final study cohort, with case numbers and percentages for each anatomical region. Percentages are based on the final analyzed cohort (n=32). LVOT: Left ventricular outflow tract, RVOT: Right ventricular outflow tract, LCC: Left coronary cusp, MV: Mitral valve, AMC: Aortomitral continuity, PPM: Posteromedial papillary muscle, LPF: Left posterior fascicle, L-RCC: Left-right coronary cusp commissure

Table 3. Diagnostic performance of algorithms targeting RVOT-LVOT distinction

	The V2S/V3R index n=26	The V2 transition ratio n=21	R-wave duration index n=18	
Metric	Value (95% CI)			
Overall accuracy	80.8% (62.1–91.5)	61.9% (40.9–79.2)	72.2% (49.1–87.5)	
Sensitivity	85.7% (60.1–96.0)	61.5% (35.5–82.3)	16.7% (3.0–56.4)	
Specificity	75.0% (46.8–91.1)	62.5% (30.6–86.3)	100.0% (75.8–100)	
Positive predictive value	80.0% (54.8–93.0)	72.7% (43.4–90.3)	100.0% (20.7–100)	
Negative predictive value	81.8% (52.3–94.9)	50.0% (23.7–76.3)	70.6% (46.9–86.7)	
Cohen's kappa	0.61	0.23	0.21	
	Count			Description
True positives	12	8	1	Algorithm predicted LVOT (ASC/LVOT in RwDI); EP confirmed LVOT (ASC/LVOT in RwDI)
True negatives	9	5	12	Algorithm predicted RVOT ("Not aortic cusp" in RwDI); EP confirmed RVOT (RVOT/other in RwDI)
False positives	3	3	0	Algorithm predicted LVOT (ASC/LVOT in RwDI); EP confirmed RVOT (RVOT/other in RwDI)
False negatives	2	5	5	Algorithm predicted RVOT ("Not aortic cusp" in RwDI); EP confirmed LVOT (ASC/LVOT in RwDI)

LVOT: Left ventricular outflow tract, RVOT: Right ventricular outflow tract, V2S/V3R: Ratio of S-wave amplitude in lead V2 to R-wave amplitude in lead V3, CI: Confidence interval, ASC: Aortic sinus cusp, RwDI: R-wave duration index, EP: Electrophysiological

A complete-case sensitivity analysis was performed in the 14 patients in whom the V2S/V3R index, V2 Transition ratio, and RwdI were all applicable. In this matched subset, the V2S/V3R index remained the most numerically accurate algorithm, with 78.6% accuracy, 83.3% sensitivity, and 75.0% specificity. The V2 Transition ratio showed 57.1% accuracy, 50.0% sensitivity, and 62.5% specificity. The RwdI demonstrated an accuracy of 64.3%, a sensitivity of 16.7%, and a specificity of 100.0% in identifying aortic cusp origins. Pairwise exact McNemar comparisons did not show significant differences between the V2S/V3R index and V2 transition ratio ($p=0.453$), V2S/V3R index and RwdI ($p=0.688$), or V2 transition ratio and RwdI ($p=1.000$).

Chance-corrected agreement was substantial for the V2S/V3R index (κ : 0.61) and fair for both the V2 transition ratio (κ : 0.23) and the RwdI (κ : 0.21).

The Algorithm Proposed by Yamada et al. (3)

Unlike the previously analyzed models, which were restricted to differentiating between outflow tracts or identifying specific aortic cusps, this algorithm is a comprehensive 12-lead ECG tool designed to

localize idiopathic PVC origins across the entire heart. As a result, all 32 patients in our cohort were eligible for this analysis. The diagnostic performance of Yamada et al.'s (3) algorithm for left (LVOT) vs. right (RVOT) localization, including accuracy, sensitivity, specificity, PPV, and NPV, is presented in Table 4.

Because the algorithm predicts highly specific sub-regional locations (e.g., distinguishing between anterior RVOT, specific cusps, or mitral valve regions), we evaluated its performance at two distinct levels: binary lateralization (left-sided/LVOT vs. right-sided/RVOT) and exact sub-regional localization.

4-Step Algorithm Proposed by Enriquez et al. (10)

The final model in our analysis is the 4-step algorithm proposed by Enriquez and colleagues. Similar to Yamada, this algorithm attempts to predict the specific regional origin of the PVC and is evaluated based on strict regional concordance. In our dataset, it was applied to all 32 patients without exclusions. The diagnostic performance of the Enriquez et al. (10) algorithm for left-/LVOT vs. right-/RVOT localization, including accuracy, sensitivity, specificity, PPV, and NPV, is presented in Table 5.

Table 4. Diagnostic performance of the Yamada et al. (3) algorithm for left-/LVOT vs. right-/RVOT localization

Yamada et al. (3) (n=32)		
Metric	Value (95% CI)	Description
Overall Accuracy	87.5% (71.9–95.0)	
Sensitivity	90% (69.9–97.2)	
Specificity	83.3% (55.2–95.3)	
Positive predictive value	90.0% (69.9–97.2)	
Negative predictive value	83.3% (55.2–95.3)	
Cohen's kappa	0.73	
Classification	Count	
True positives	18	Algorithm predicted left/LVOT; EP confirmed left/LVOT
True negatives	10	Algorithm predicted right/RVOT; EP confirmed right/RVOT
False positives	2	Algorithm predicted left/LVOT; EP confirmed right/RVOT
False negatives	2	Algorithm predicted right/RVOT; EP confirmed left/LVOT

LVOT: Left ventricular outflow tract, RVOT: Right ventricular outflow tract, CI: Confidence interval, EP: Electrophysiological

Table 5. Diagnostic performance of the Enriquez et al. (10) algorithm for left-/LVOT vs. right-/RVOT localization

Enriquez et al. (10) (n=32)		
Metric	Value (95% CI)	Description
Overall accuracy	56.3% (39.3–71.8)	
Sensitivity for left/LVOT origins	30% (14.5–51.9)	
Specificity for right/RVOT origins	100% (75.8–100)	
Positive predictive value (PPV)	100% (61.0–100)	
Negative predictive value (NPV)	46.2% (28.8–64.5)	
Cohen's kappa	0.24	
Classification	Count	
True positives (TP)	6	Algorithm predicted left/LVOT; EP confirmed left/LVOT
True negatives (TN)	12	Algorithm predicted right/RVOT; EP confirmed right/RVOT
False positives (FP)	0	Algorithm predicted left/LVOT; EP confirmed right/RVOT
False negatives (FN)	14	Algorithm predicted right/RVOT; EP confirmed left/LVOT

LVOT: Left ventricular outflow tract, RVOT: Right ventricular outflow tract, CI: Confidence interval, EP: Electrophysiological

Performance of Regional Prediction Algorithms

For exact regional localization, the Yamada algorithm demonstrated an overall accuracy of 81.3%, correctly identifying the specific substructural origin in 26 of 32 patients. In contrast, the Enriquez algorithm yielded a significantly lower overall accuracy of 31.3% (10 of 32 patients). A pairwise comparison using the exact McNemar’s test in the matched cohort revealed that the diagnostic performance of the Yamada algorithm was statistically superior to that of the Enriquez algorithm ($p=0.0004$). The exact regional concordance of the Enriquez et al. (10) and Yamada et al. (3) algorithms with the electrophysiologically confirmed site of origin is presented in Table 6.

For binary lateralization (left/LVOT vs.right/RVOT), agreement was substantial for the Yamada algorithm (κ : 0.73) and fair for the Enriquez algorithm (κ : 0.24).

Discussion

In this retrospective study assessing accuracy among patients who underwent successful catheter ablation for idiopathic PVCs, several important findings emerged. First, among the ECG tools primarily designed for outflow tract discrimination, the V2S/V3R index demonstrated the best overall diagnostic performance in our cohort. Second, although the RwdI demonstrated lower sensitivity, it provided excellent specificity for identifying a non-aortic cusp origin. Third, among the two comprehensive localization approaches, the algorithm proposed by Yamada et al. (3) substantially outperformed the 4-step algorithm proposed by Enriquez et al. (10) for exact regional localization.

Among the right–left outflow tract discrimination algorithms, the V2S/V3R index showed the best overall diagnostic performance in our cohort. On closer examination of the data, the algorithm predicted an LVOT origin in three patients, but their successful ablation sites were right-sided. Two of these sites were located in the posterior RVOT, and one was located in the right para-Hisian region. Anatomically, these right-sided structures lie close to the septal border of the LVOT, which may produce pseudo-left-sided ECG patterns. In the original study by Yoshida et al. (4), a cut-off value of ≤ 1.5 predicted an LVOT origin with 89% sensitivity and 94% specificity. In our cohort, however, the V2S/V3R index demonstrated a sensitivity of 85.7% and a specificity of 75.0% for left-sided origins, with a PPV of 80.0% and a NPV of 81.8%. Although both sensitivity and specificity were lower than those reported in the original study, the V2S/V3R index remained the most accurate parameter among those evaluated in our analysis, which is consistent with the findings of the original report (4). The complete-case sensitivity analysis reduced the potential bias introduced by unequal algorithm-specific denominators.

In this matched subset, the V2S/V3R index remained numerically higher, consistent with the main analysis. However, the absence of statistically significant pairwise differences should be interpreted with caution, because only 14 patients were eligible for all three binary indices.

The physiological basis of this index is that the aortic sinuses and the LVOT are located deeper and more posteriorly than the RVOT, resulting in a relatively higher R-wave amplitude in lead V3 and relatively lower S-wave amplitudes in leads V1 and V2. Although the V2 transition ratio was developed as an anatomically refined index that accounts for cardiac rotation, respiratory variation, and interindividual anatomical differences, its performance in our cohort was modest. While Betensky et al. (6) reported that a V2 transition ratio ≥ 0.6 predicted an LVOT origin with 95% sensitivity and 100% specificity in their original article, Yoshida et al. (4) found lower values, with a sensitivity of 81% and a specificity of 61%. In our series limited to patients with a V3 transition pattern, the corresponding sensitivity and specificity were 61.5% and 62.5%, respectively. It proved particularly unreliable for predicting RVOT for structures deep within the LVOT [left-right coronary cusp commissure (L-RCC), left coronary cusp (LCC), and summit], resulting in a very low NPV (50.0%). Detailed analysis of our data revealed that most false-positive and false-negative classifications originated in anatomically challenging regions near the contralateral side, particularly the posterior RVOT, the coronary cusps, and the summit.

The RwdI, first described by Ouyang et al. (9) in a 15-patient study, was found by Yoshida et al. (4) to have a sensitivity of 45% and a specificity of 92%. In the subgroup of patients with a precordial PVC transition at V3, sensitivity was shown to decline further to 31% (4,9). Although our results were broadly consistent with previous findings, the RwdI showed notably low sensitivity in our cohort, despite a specificity of 100%. The main limitation of this index was its inability to identify true aortic cusp origins: five patients with electrophysiologically confirmed cusp foci—three from the L-RCC commissure and two from the left coronary cusp—were misclassified as having an RVOT origin. Therefore, while a positive RwdI finding strongly supports an aortic cusp origin, a negative result does not reliably exclude it.

The Yamada algorithm performed exceptionally well in our cohort. It not only successfully lateralized the arrhythmia in 87.5% of patients but also achieved exact regional concordance in 81.3% of the cohort. As with prior algorithms, the primary vulnerability of this algorithm lies at the deep septal border (posterior RVOT masquerading as left/summit structures and vice versa). An additional noteworthy aspect of our findings is that, to our knowledge, the review-based whole-heart localization scheme proposed by Yamada et al. (3) has not previously been validated as a

Table 6. Exact regional concordance of the Enriquez et al. (10) and Yamada et al. (3) algorithms with the electrophysiologically confirmed site of origin

	Overall accuracy	Value (n=32)	Description
Enriquez et al. (10)	Exact regional concordance	10 (31.3%)	Algorithm exactly matched the EP-confirmed site
	Discordance (error)	22 (68.8%)	Algorithm missed the exact sub-regional origin
Yamada et al. (3)	Exact regional concordance	26 (81.3%)	Algorithm exactly matched the EP-confirmed site
	Discordant cases	6 (18.8%)	Algorithm missed the exact sub-regional origin

EP: Electrophysiological

single, comprehensive diagnostic algorithm with globally reported sensitivity, specificity, or accuracy. The 2019 publication by Yamada et al. (3) is a review that summarizes ECG approaches for localizing idiopathic PVC origins and discusses their caveats, rather than being an original validation study reporting unified performance metrics for the entire algorithmic framework. In this context, our study provides clinically relevant validation data for the Yamada approach (3).

Among the localization tools evaluated in this study, the four-step algorithm proposed by Enriquez et al. (10) showed the lowest performance, with an exact regional accuracy of 31.3%. Its principal weakness was a marked underdetection of left-sided origins, particularly LVOT cusps and LV summit foci, which were frequently misclassified as anterior RVOT or other right-sided structures. Although left-sided predictions were highly reliable when explicitly made, the algorithm demonstrated a clear tendency to default challenging left-sided substrates to right-sided categories. This pattern suggests that the algorithm may be more useful for broad bedside orientation than for precise preprocedural localization in anatomically complex idiopathic PVCs (10).

Recurrence occurred in 10 of 30 patients with available follow-up (33.3%). This is higher than the ~15–25% long-term recurrence commonly reported after idiopathic PVC ablation, and most plausibly reflects the anatomically complex composition of our cohort, which was enriched for technically demanding origins, LV summit, coronary cusps, and papillary muscles, that carry lower acute success and higher recurrence than the RVOT (11,12). Notably, late recurrence in this setting frequently arises from a site remote from the index focus rather than from the originally targeted region (13).

Clinical Utility and Incremental Value

Beyond their diagnostic metrics, preprocedural ECG algorithms have practical implications for procedural planning and patient counseling. Reliable lateralization informs the anticipated access strategy (retrograde aortic or transseptal access for left-sided origins vs. a right-sided approach), prompts pre-emptive coronary angiography when an aortic cusp or LV summit origin is suspected, and flags cases in which an epicardial or coronary-venous approach may be required, thereby indicating the need for referral to a high-volume center. It also enables individualized counseling, because expected acute success and complication risk differ substantially between, for example, the RVOT and the LV summit (12). That said, the incremental value of these algorithms over an experienced operator's gestalt was not directly assessed in the present study; structured algorithms are likely most useful for less-experienced operators, for trainee education, and as reproducible adjuncts, and may be further augmented by emerging automated and machine-learning-based localization tools and noninvasive ECG imaging (14). Prospective evaluation is warranted to determine whether algorithm-guided planning measurably changes access strategy, procedure duration, or outcomes.

Although the overall cohort size in our study ($n=32$) may appear modest, this is consistent with historical methodology used in

ventricular arrhythmia localization research. Many of the pioneering and now widely accepted ECG criteria for idiopathic PVC localization were originally derived and validated in similarly sized or even smaller cohorts. For example, the seminal study by Ouyang et al. describing ECG characteristics for ablation of repetitive monomorphic ventricular tachycardia from the ASC was based on only 15 patients (9). Subsequent foundational work, including early descriptions of the precordial transition zone, the V2 transition ratio, and the R-wave deflection interval, was likewise derived from cohorts of fewer than 50 patients (6,7). This precedent reflects the focal and relatively uncommon nature of these arrhythmias and the considerable time and procedural resources required to assemble series that are accurately localized and ablation-confirmed. While these historical considerations do not eliminate the limitations of a small cohort, they support the validity of small, well-characterized validation studies, a recognized methodological tradition in this field, and justify the role of the present study as a hypothesis-generating contribution to the comparative evaluation of established algorithms.

Study Limitations

This study has several limitations. It was a single-center retrospective study with a relatively small sample size ($n=32$). Moreover, because several of the evaluated algorithms were applicable only to specific morphological subgroups, individual analyses were based on as few as 14 patients. As a result, the diagnostic performance estimates are imprecise, with correspondingly wide 95% confidence intervals (Tables 3-5), and the present findings should be regarded as hypothesis-generating rather than confirmatory. In particular, the absence of external validation in an independent, ideally multicenter, cohort is a key limitation. Only five ECG algorithms were assessed, and the inclusion of a broader range of previously proposed ECG criteria might have allowed a more comprehensive evaluation. Prospective validation in larger multicenter populations is therefore required before these comparative observations can be translated into routine clinical practice.

Conclusion

In patients undergoing catheter ablation for idiopathic PVCs, ECG algorithms differed substantially in their ability to predict the successful ablation site. The V2S/V3R index was the most useful discriminator for right-left outflow tract origin, whereas the R_wDI provided excellent specificity but poor sensitivity for aortic cusp identification. The Yamada algorithm demonstrated the best overall performance for comprehensive localization and may represent a useful preprocedural whole-heart ECG tool. These findings support selective rather than uniform use of ECG algorithms, depending on the specific clinical localization question.

Ethics

Ethics Committee Approval: The study complied with the Declaration of Helsinki and received approval from the Izmir City Hospital Institutional Review Board (decision number: 2025/522, date: 16.10.2025).

Informed Consent: Due to the retrospective nature of the study, informed consent was not obtained from the patients.

Footnotes

Authorship Contributions: Surgical and Medical Practices - S.E., H.G.U.; Concept - S.E.; Design - S.E.; Data Collection or Processing - S.E., H.G.U.; Analysis or Interpretation - S.E., H.G.U.; Literature Search - S.E.; Writing - S.E., H.G.U.

Conflict of Interest: No conflict of interest was declared by the authors.

Financial Disclosure: The authors declared that this study received no financial support.

References

- Zeppenfeld K, Tfelt-Hansen J, de Riva M, Winkel BG, Behr ER, Blom NA, et al. 2022 ESC Guidelines for the management of patients with ventricular arrhythmias and the prevention of sudden cardiac death. *Eur Heart J*. 2022; 43: 3997-4126.
- Ling Z, Liu Z, Su L, Zipunnikov V, Wu J, Du H, et al. Radiofrequency ablation versus antiarrhythmic medication for treatment of ventricular premature beats from the right ventricular outflow tract: prospective randomized study. *Circ Arrhythm Electrophysiol*. 2014; 7: 237-43.
- Yamada T. Twelve-lead electrocardiographic localization of idiopathic premature ventricular contraction origins. *J Cardiovasc Electrophysiol*. 2019; 30: 2603-17.
- Yoshida N, Yamada T, McElderry HT, Inden Y, Shimano M, Murohara T, et al. A novel electrocardiographic criterion for differentiating a left from right ventricular outflow tract tachycardia origin: the V2S/V3R index. *J Cardiovasc Electrophysiol*. 2014; 25: 747-53.
- Ito S, Tada H, Naito S, Kurosaki K, Ueda M, Hoshizaki H, et al. Development and validation of an ECG algorithm for identifying the optimal ablation site for idiopathic ventricular outflow tract tachycardia. *J Cardiovasc Electrophysiol*. 2003; 14: 1280-6.
- Betensky BP, Park RE, Marchlinski FE, Hutchinson MD, Garcia FC, Dixit S, et al. The V(2) transition ratio: a new electrocardiographic criterion for distinguishing left from right ventricular outflow tract tachycardia origin. *J Am Coll Cardiol*. 2011; 57: 2255-62.
- Cheng Z, Cheng K, Deng H, Chen T, Gao P, Zhu K, et al. The R-wave deflection interval in lead V3 combining with R-wave amplitude index in lead V1: a new surface ECG algorithm for distinguishing left from right ventricular outflow tract tachycardia origin in patients with transitional lead at V3. *Int J Cardiol*. 2013; 168: 1342-8.
- Di C, Wan Z, Tse G, Letsas KP, Liu T, Efremidis M, et al. The V₁-V₃ transition index as a novel electrocardiographic criterion for differentiating left from right ventricular outflow tract ventricular arrhythmias. *J Interv Card Electrophysiol*. 2019; 56: 37-43.
- Ouyang F, Fotuhi P, Ho SY, Hebe J, Volkmer M, Goya M, et al. Repetitive monomorphic ventricular tachycardia originating from the aortic sinus cusp: electrocardiographic characterization for guiding catheter ablation. *J Am Coll Cardiol*. 2002; 39: 500-8.
- Enriquez A, Baranchuk A, Briceno D, Saenz L, Garcia F. How to use the 12-lead ECG to predict the site of origin of idiopathic ventricular arrhythmias. *Heart Rhythm*. 2019; 16: 1538-44.
- Anderson RD, Kumar S, Parameswaran R, Wong G, Voskoboinik A, Sugumar H, et al. Differentiating right- and left-sided outflow tract ventricular arrhythmias: classical ECG signatures and prediction algorithms. *Circ Arrhythm Electrophysiol*. 2019; 12: e007392.
- Gulletta S, Gasperetti A, Schiavone M, Paglino G, Vergara P, Compagnucci P, et al. Long-term follow-up of catheter ablation for premature ventricular complexes in the modern era: the importance of localization and substrate. *J Clin Med*. 2022; 11: 6583.
- Lee D, Hoffmayer KS, Hsu JC, Schricker A, Birgersdotter-Green U, Raissi F, et al. Long-term mode and timing of premature ventricular complex recurrence following successful catheter ablation. *J Interv Card Electrophysiol*. 2019; 55: 153-60.
- Nakasone K, Nishimori M, Shinohara M, Takami M, Imamura K, Nishida T, et al. Enhancing origin prediction: deep learning model for diagnosing premature ventricular contractions with dual-rhythm analysis focused on cardiac rotation. *Europace*. 2024; 26: euae240.