The Heart Surgery Forum

Heart Surg. Forum **2026**; 29(7): 51841
https://doi.org/10.31083/HSF51841

Article

Impact of Radiofrequency Ablation on Biventricular Myocardial Strain in Patients With Idiopathic Right Ventricular Outflow Tract Premature Ventricular Contractions: A Prospective Pre–Post Speckle-Tracking Echocardiography Study

Ardi Yudha[1], Rille Puspitoadhi Harjoko[1,2], Aruman Yudanto Aribowo Binarso Mochtar[1,2], Henry Setyawan[3], Susi Herminingsih[1,2], Pipin Ardhianto[1,2,*]

[1]Department of Cardiology and Vascular Medicine, Faculty of Medicine, Universitas Diponegoro, 50275 Semarang, Indonesia
[2]Department of Cardiovascular, Dr. Kariadi General Hospital, 50244 Semarang, Indonesia
[3]Faculty of Public Health, Universitas Diponegoro, 50275 Semarang, Indonesia
*Correspondence: pipinardhianto@fk.undip.ac.id (Pipin Ardhianto)
Academic Editor: Tadahisa Sugiura
Submitted: 13 March 2026 Revised: 4 May 2026 Accepted: 8 May 2026 Published: 23 July 2026

Abstract

Background: Idiopathic premature ventricular contractions (PVCs) originating from the right ventricular outflow tract (RVOT) are associated with subclinical ventricular dysfunction despite preserved conventional systolic indices. Indeed, several studies have shown that speckle-tracking echocardiography (STE) enables sensitive assessment of longitudinal myocardial mechanics and may detect early functional recovery after catheter ablation. **Methods:** This pre–post observational study included 26 adults with an idiopathic RVOT PVC burden >15% who underwent catheter ablation. A STE and 24-hour Holter monitoring were performed at baseline and 3 months to assess left ventricular global longitudinal strain (LV-GLS), right ventricular free-wall longitudinal strain (RVFWLS), and right ventricular four-chamber longitudinal strain (RV4CLS). Associations between PVC burden reduction (ΔPVC%) and changes in strain were evaluated using correlation analyses, threshold-based comparisons, and exploratory multiple linear regression models adjusted for baseline strain and baseline PVC burden. **Results:** The study included 26 patients with a mean age of 46.7 ± 10.4 years; 23 patients (88.5%) were women. PVC burden decreased from a median of 20.5% (interquartile range [IQR] 17.8–20.5) at baseline to 1.5% (IQR 1–5.3) at 3 months. Furthermore, all strain indices improved significantly, including LV-GLS (−17.8 ± 3.4 to −20.9 ± 3.5), RVFWLS (−23.1 ± 4.3 to −28.3 ± 4.3), and RV4CLS (−18.9 ± 3.8 to −23.3 ± 3.6) (all $p < 0.001$). Greater ΔPVC% correlated with recovery in LV-GLS (Spearman's rs = −0.51; $p = 0.008$) and RVFWLS (Spearman's rs = −0.49; $p = 0.010$), but not with RV4CLS. Patients achieving a ΔPVC% ≥80% demonstrated greater improvement in LV-GLS and RVFWLS. In exploratory multiple linear regression models, ΔPVC% remained associated with recovery in LV-GLS and RVFWLS, but not with RV4CLS. **Conclusions:** Catheter ablation of idiopathic RVOT PVCs was associated with significant improvement in biventricular longitudinal strain at 3 months. A higher reduction in PVC burden was associated with greater improvements in LV-GLS and RVFWLS, suggesting that suppression of ectopic burden may be linked to early mechanical recovery. Given the observational pre–post design and modest sample size, these findings should be interpreted as associative and hypothesis-generating.

Keywords: premature ventricular contractions; catheter ablation; speckle-tracking echocardiography; global longitudinal strain; right ventricular free-wall longitudinal strain; right ventricular four-chamber longitudinal strain

1. Introduction

Premature ventricular contractions (PVCs) originating from the right ventricular outflow tract (RVOT) are the most common idiopathic ventricular arrhythmia in patients without structural heart disease, accountable for 60–80% of idiopathic PVC [1]. Although PVCs are often considered benign when left ventricular ejection fraction (LVEF) is preserved, a high burden may lead to ventricular dysfunction, particularly subclinical dysfunctionthat can not be detected by conventional parameters except through speckle-tracking echocardiography (STE) [2].

Frequent PVCs contribute to increased wall stress, electrical-mechanical dyssynchrony, and reduced contractile efficiency, potentially progressing to PVC-induced cardiomyopathy, a condition that is often reversible after effective suppression [3,4]. Most guidelines and reviews consider PVC burden ≥10% as a level where PVC-induced cardiomyopathy can be suspected [1,5,6]. Apart from the left ventricle (LV), idiopathic RVOTPVCs may also impair the right ventricle (RV). This is in line with previous studies showing reduced RV strain despite preserved LVEF and cardiac magnetic resonance (CMR) studies suggesting potential biventricular involvement [7,8].

According to previous reports, catheter ablation is effective in reducing PVC burden and improving ventricular function, with long-term success commonly defined as a

reduction ≥80% at 3–6 months follow-up [9,10]. Although improvement in left ventricular global longitudinal strain (LV-GLS) after PVC suppression has been described previously [2], data regarding biventricular mechanical recovery, particularly RV strain recovery after ablation of idiopathic RVOT PVCs, remain limited [7,8]. Due to the origination of ectopic focus from RVOT, repetitive abnormal activation may directly affect RV mechanics [7]. In addition, PVCs may influence LV deformation through ventricular interdependence, septal motion, and altered biventricular loading conditions [8,9]. This indicates that simultaneous assessment of LV and RV strain may provide a more comprehensive evaluation of early mechanical recovery after ablation.

In this context, right ventricular free-wall longitudinal strain (RVFWLS) may reflect RV systolic mechanics, while right ventricular four-chamber longitudinal strain (RV4CLS) includes septal segments and can be more influenced by interventricular interaction. Therefore, this study aims to evaluate pre-post changes in biventricular strain parametersat 3 months following catheter ablation of idiopathic RVOT PVCs and to explore the association between PVC burden reduction and strain recovery.

2. Methods

2.1 Study Design and Setting

This pre-post observational cohort study was conducted at Dr. Kariadi General Hospital. Consecutive eligible patients undergoing catheter ablation for idiopathic RVOT PVCs were enrolled after providing written informed consent. This study aimed to evaluate pre-post changes in biventricular strain after ablation and to explore the association between PVC burden reduction and strain recovery. No separate control group receiving antiarrhythmic drug therapy alone was included. Therefore, the analysis was limited to within-patient pre-post comparisons after catheter ablation.

2.2 Participants

Inclusion criteria included age ≥18 years, idiopathic RVOT PVCs suspected by 12-lead electrocardiogram (ECG) morphology and confirmed during radiofrequency ablation by the target site documented in 2 orthogonal fluoroscopic views, baseline PVC burden >15% on pre-ablation 24-hour Holter monitoring, and willingness as well as ability to complete 3-month follow-up testing. Exclusion criteria were (1) non-sinus baseline rhythm; multifocal PVCs without a dominant morphology; (2) prior PVC ablation; (3) structural heart disease (confirmed by clinical assessment and baseline echocardiography, including history of acute coronary syndrome, heart failure, significant valvular disease, or congenital heart disease); (4) hyperthyroidism; (5) chronic obstructive pulmonary disease or pulmonary hypertension; and (6) inadequate echocardiographic image quality precluding strain analysis.

2.3 Mapping and Ablation

In this study, all procedures were performed without sedation. Antiarrhythmic drugs (AADs) were discontinued for 5 half-lives before the procedure. All PVC mapping and ablation procedures were performed using a 2D approach with the Labsystem™ PRO EP Recording System from Boston Scientific (Boston Scientific Corporation, Marlborough, Massachusetts, USA), along with the Blazer™ HTD Temperature Ablation Catheter (Boston Scientific Corporation, Marlborough, Massachusetts, USA) or Blazer™ Open Irrigated Temperature Ablation Catheter (Boston Scientific Corporation, Marlborough, Massachusetts, USA) as per institutional standards.

All patients were observed to have clinical PVCs during the procedure. Activation mapping was performed and complemented by pace mapping during sinus rhythm to localize the PVC origin. In addition, radiofrequency energy was delivered in temperature-controlled mode (target 55 °C, 30 W). When PVCs were suppressed within 20 seconds, ablation was continued for 60 to 90 seconds, followed by an additional 60-second consolidation application. In case of no suppression, energy delivery was stopped after 25 to 30 seconds, and remapping or switching to an irrigated ablation catheter was performed. The final target site was documented in 2 orthogonal fluoroscopic views. Acute success was defined as the absence of PVCs with the same clinical morphology during a 30-minute observation period.

2.4 Holter Analysis and PVC Burden Reduction

PVC burden was calculated as the percentage of PVC beats among total beats on 24-hour Holter recordings obtained at baseline and at 3 months after ablation. Holter recordings were analyzed using standardized software (BTL-08 Holter system, BTL Industries Limited, Stevenage, Hertfordshire, UK), and PVC counts were reviewed and verified by an experienced electrophysiologist/cardiologist. PVC burden reduction was expressed as ΔPVC% = (PVC burden at baseline – PVC burden at 3-months)/PVC burden at baseline × 100%. A reduction of ≥80% at 3 months was prespecified to represent substantial burden reduction, consistent with prior ablation literature. Patients were categorized into 2 groups based on ΔPVC% at 3 months (<80% vs ≥80%) for comparative analyses of strain improvement.

2.5 Echocardiography

A 2-dimensional transthoracic echocardiography was performed using a commercially available ultrasound system (EPIQ CVx, Philips Medical Systems, Andover, MA, USA) equipped with a phased-array transducer. Image acquisition was conducted using standard parasternal and apical views, with an imaging depth adjusted according to body habitus (approximately 16 cm). Standard M-mode, grayscale 2-dimensional, and color Doppler images were obtained with ECG gating and stored in cine-loop format

for subsequent offline analysis using dedicated workstation software. The same acquisition protocol was applied at baseline and follow-up. For STE analysis, images were acquired with an optimized frame rate (typically 50 to 90 frames/s) whenever feasible. LVEF was measured using the biplane Simpson's method. All echocardiographic measurements were performed on remote sinus beats, and the first post-extrasystolic beat was excluded whenever feasible to minimize post-ectopic augmentation effects.

2.6 Speckle-Tracking Echocardiography

Speckle-tracking echocardiography (STE) was performed at baseline and at 3-month follow-up. LV-GLS was derived from apical 4-, 2-, and 3-chamber views using standardized post-processing. RV strain was assessed from an RV-focused apical 4-chamber view. RVFWLS and RV4CLS were measured using standardized post-processing protocols. RVFWLS was calculated as the average longitudinal strain of the right ventricular free-wall segments (basal, mid, and apical), while RV4CLS was calculated from the entire right ventricular 4-chamber myocardium, including septal segments. Measurements were averaged over 3 consecutive cardiac cycles when feasible. All echocardiographic image acquisition was performed by a single operator. Strain analysis was performed offline using vendor-specific software (Philips QLAB, Philips Medical Systems). Inter-observer reliability was evaluated on a randomly selected sample, independently analyzed by 2 observers, using intraclass correlation coefficients (ICC). In addition, ICCs were calculated using an absolute-agreement model.

2.7 Follow-Up

Follow-up testing was scheduled 70 to 120 days after the procedure and included 24-hour Holter monitoring and repeat STE using the same acquisition protocol as at baseline. Symptom status was assessed clinically during follow-up based on residual or recurrent symptoms, including palpitations, dizziness, near syncope, or syncope. No standardized symptom score or quality-of-life instrument was used. AADs used for PVC suppression, including β-blockers when prescribed primarily for arrhythmia control, were discontinued after successful ablation because there was no clinical indication to continue AADs during follow-up. Background cardiovascular medications, including angiotensin-converting enzyme inhibitors, angiotensin receptor blockers, and calcium-channel blockers, were continued without protocol-driven intervention or modification during the follow-up period, unless modification was deemed clinically necessary.

2.8 Outcomes

The primary outcome was the pre-post change in biventricular longitudinal strain indices at 3 months following catheter ablation, assessed by STE parameters including LV-GLS, RVFWLS, and RV4CLS. Secondary outcomes were (1) the association between PVC burden reduction (ΔPVC%) and changes in strain parameters (ΔLV-GLS, ΔRVFWLS, and ΔRV4CLS); and (2) comparison of strain recovery between patients with ΔPVC% ≥80% and those with ΔPVC% <80% at follow-up. Changes in strain parameters (Δ) were calculated as follow-up values minus baseline values (e.g., ΔLV-GLS = LV-GLS at 3 months − LV-GLS at baseline; similarly for ΔRVFWLS and ΔRV4CLS). More negative LV-GLS and RV strain values showed better systolic myocardial deformation. Accordingly, a negative Δ value reflected strain improvement, while a positive Δ value reflected worsening.

2.9 Statistical Analysis

Analyses were performed using IBM SPSS Statistics Version 25 (IBM Corp., Armonk, NY, USA), and continuous variables were presented as mean ± SD or median (IQR) as appropriate, then categorical variables were shown as n (%). Normality was assessed using the Shapiro–Wilk test, and paired comparisons used paired *t*-tests or Wilcoxon signed-rank tests. Correlations used Pearson or Spearman methods based on distribution and linearity, which was denoted as r_s. Between-group comparisons (ΔPVC% <80% vs ≥80%) using independent *t*-tests or Mann–Whitney U tests. For association and regression analyses, changes in strain indices were expressed as absolute differences (Δ), calculated as follow-up minus baseline values (3 months – baseline). Simple linear regression was used for univariable analyses to examine the association between each potential predictor and changes in strain parameters. Variables with $p < 0.25$ in simple linear regression and variables considered clinically relevant were considered for entry into multiple linear regression models. Due to the limited sample size, multiple linear regression models were intentionally restricted to 3 clinically relevant predictors to reduce the risk of overfitting. For each strain outcome, the model included PVC burden reduction, the corresponding baseline strain value, and baseline PVC burden. These models were considered exploratory and were used to assess whether the observed associations remained directionally consistent after adjustment for key baseline variables. Regression coefficients were reported as estimated unstandardized coefficients, denoted as b, with 95% confidence intervals, and a 2-sided $p < 0.05$ was considered statistically significant.

3. Results

3.1 Participants and Baseline Characteristics

Among 26 patients with idiopathic RVOT PVCs and baseline PVC burden >15%, the mean age was 46.7 ± 10.4 years, and 88.5% were women. At baseline, 24 patients were symptomatic, and 2 patients were asymptomatic. Palpitations were the most common presenting symptom (80.8%). During the procedures, symptom duration was 24 months (IQR 12–48 months). Baseline PVC

burden decreased from a median of 20.5% (IQR 17.8–20.5) to 1.5% (IQR 1–5.3) at 3 months, and 20 patients (76.9%) achieved ΔPVC% ≥80%. At the 3-month follow-up, all symptomatic patients reported improvement, with no residual symptoms reported after ablation. These data were considered descriptive because symptom status was assessed clinically without a standardized symptom score or quality-of-life instrument.

Regarding PVC characteristics, a PVC QRS complex (QRS) duration >150 ms was observed in 19.2%, interpolated PVCs in 7.7%, and a coupling interval <400 ms in 23.1% of patients (Table 1). Baseline medication use is summarized in Table 1. After successful ablation, AADs used for PVC suppression, including β-blockers when prescribed for arrhythmia control, were discontinued in all patients. Background cardiovascular medications, including angiotensin-converting enzyme inhibitors, angiotensin receptor blockers, and calcium-channel blockers, were continued without protocol-driven changes.

3.2 Pre-Post Changes in Biventricular Strain

According to this study, 3 months following catheter ablation, all biventricular strain indices showed significant recovery, reflected by more negative (improved) longitudinal strain values. LV-GLS improved from −17.8 ± 3.4 to −20.9 ± 3.5 (paired *t*-test; mean ΔLV-GLS = −3.2, 95% CI −4.4 to −1.9; $p < 0.001$). RVFWLS improved from −23.1 ± 4.3 to −28.3 ± 4.3 (Wilcoxon signed-rank test, Z = −4.08; $p < 0.001$). Similarly, RV4CLS improved from −18.9 ± 3.8 to −23.3 ± 3.6 (Wilcoxon signed-rank test, Z = −4.18; $p < 0.001$) (Fig. 1).

3.3 Association Between PVC Burden Reduction and Strain Recovery

Greater PVC burden reduction (ΔPVC%) was significantly associated with strain recovery. ΔPVC% correlated with ΔLV-GLS 8(Spearman's $r_s = -0.51$; $p = 0.008$) and ΔRVFWLS (Spearman's $r_s = -0.49$; $p = 0.010$), showing that a larger reduction in PVC burden was associated with a greater degree of strain improvement. However, no significant association was observed between ΔPVC% and ΔRV4CLS (Spearman's $r_s = -0.24$; $p = 0.246$) (Table 2).

3.4 Comparison by PVC Burden Reduction Threshold

When patients were stratified by a prespecified PVC burden reduction threshold, those achieving ΔPVC% ≥80% (n = 20) had greater strain recovery compared to those with ΔPVC% <80% (n = 6). The change in LV-GLS (ΔLV-GLS) was significantly larger (more negative) in the ΔPVC% ≥80% group than in the ΔPVC% <80% group (−3.9 ± 2.5 vs −0.7 ± 2.9; Mann–Whitney U = 22.0; Z = −2.315; $p = 0.021$). ΔRVFWLS was significantly greater in the ΔPVC% ≥80% group compared to ΔPVC% <80% (−6.4 ± 5.0 vs −1.3 ± 3.3; Mann–Whitney U = 22.0; Z = −2.314; $p = 0.021$). However, ΔRV4CLS did not differ significantly between groups (−4.8 ± 4.9 vs −3.6 ± 2.2; U = 53.5; Z = −0.396; $p = 0.692$), suggesting comparable RV 4-chamber longitudinal recovery across strata (Table 3).

3.5 Multivariable Regression

For ΔLV-GLS, the exploratory multiple linear regression model including ΔPVC%, baseline LV-GLS, and baseline PVC burden was statistically significant ($R^2 = 0.333$; adjusted $R^2 = 0.242$; $p = 0.028$). In the adjusted model, ΔPVC% was associated with ΔLV-GLS (b = −0.055; $p = 0.028$). Baseline LV-GLS showed a borderline association (b = −0.306; $p = 0.065$), while baseline PVC burden was not statistically significant ($p = 0.163$) (Table 4).

In ΔRVFWLS, the exploratory multiple linear regression model including ΔPVC%, baseline RVFWLS, and baseline PVC burden was also statistically significant ($R^2 = 0.465$; adjusted $R^2 = 0.392$; $p = 0.003$). In the adjusted model, ΔPVC% was associated with ΔRVFWLS (b = −0.072; $p = 0.044$). Baseline RVFWLS was also associated with strain change (b = −0.663; $p = 0.002$), while baseline PVC burden was not statistically significant ($p = 0.483$) (Table 4).

For ΔRV4CLS, the exploratory multiple linear regression model including ΔPVC%, baseline RV4CLS, and baseline PVC burden was statistically significant overall ($R^2 = 0.429$; adjusted $R^2 = 0.352$; $p = 0.006$). However, ΔPVC% was not associated with ΔRV4CLS after adjustment (b = −0.036; $p = 0.245$). Baseline RV4CLS was associated with strain change (b = −0.735; $p = 0.001$), while baseline PVC burden was not statistically significant ($p = 0.420$) (Table 4).

These regression results must be interpreted cautiously, given the modest sample size, and were intended to support rather than definitively establish independent associations.

3.6 Inter-Observer Reliability

Inter-observer agreement for strain measurements was consistently good. The intraclass correlation coefficient (ICC) was 0.76 (95% CI 0.348–0.923) for pre-ablation LV-GLS and 0.84 (95% CI 0.527–0.950) for LV-GLS at 3 months. For RVFWLS, ICC values were 0.78 (95% CI 0.394–0.930) at baseline and 0.82 (95% CI 0.479–0.943) at 3 months. Similarly, RV4CLS demonstrated good reliability, with an ICC of 0.87 (95% CI 0.606–0.960) pre-ablation and 0.82 (95% CI 0.488–0.944) at 3 months.

4. Discussion

4.1 Main Results

In this prospective pre-post study of 26 patients with idiopathic RVOT PVCs followed for 3 months after catheter ablation, 3 key results were observed. First, consistent with the primaryobjective, ablation was associated with significant improvement in biventricular subclinical function, demonstrated by more negative LV-GLS, RVFWLS,

Table 1. Baseline characteristics.

Variable	n (%)	Mean ± SD	Median (IQR)
Age (years)		46.7 ± 10.4	
Gender			
Male	3 (11.5)		
Female	23 (88.5)		
Symptoms			
Palpitation			
Yes	21 (80.8)		
No	5 (19.2)		
Dizziness			
Yes	3 (11.5)		
No	23 (88.5)		
Near syncope			
Yes	8 (30.8)		
No	18 (69.2)		
Syncope			
Yes	0 (0)		
No	26 (100)		
Asymptomatic status			
Yes	2 (7.7)		
No	24 (92.3)		
Others			
Yes	5 (19.2)		
No	21 (80.8)		
Symptom duration (months)			24 (12–48)
Comorbidities			
Hypertension			
Yes	9 (34.6)		
No	17 (65.4)		
Diabetes			
Yes	2 (7.7)		
No	24 (92.3)		
Dyslipidemia			
Yes	0 (0)		
No	26 (100)		
Lifestyle			
Low physical activity			
Yes	25 (96.2)		
No	1 (3.8)		
Smoker			
Yes	0 (0)		
No	26 (100)		
Medical treatment			
ACE-inhibitor			
Yes	5 (19.2)		
No	21 (80.8)		
Beta-blocker			
Yes	24 (92.3)		
No	2 (7.7)		
Ca-channel blocker			
Yes	2 (7.7)		
No	24 (92.3)		
Amiodarone			
Yes	1 (3.8)		

Table 1. Continued.

Variable	n (%)	Mean ± SD	Median (IQR)
No	25 (96.2)		
PVC characteristics			
Pre-ablation PVC burden (%)			20.5 (17.8–20.5)
3 months post-ablation PVC burden (%)			1.5 (1–5.3)
PVC QRS duration >150 ms			
Yes	5 (19.2)		
No	21 (80.8)		
Interpolated PVCs			
Yes	2 (7.7)		
No	24 (92.3)		
Coupling interval <400 ms			
Yes	6 (23.1)		
No	20 (76.9)		
Low circadian variability			
Yes	15 (65.2)		
No	8 (34.8)		
Subclinical echocardiographic parameters			
Pre-ablation LV-GLS		−17.8 ± 3.4	
3 months post-ablation LV-GLS		−20.9 ± 3.5	
Pre-ablation RVFWLS		−23.1 ± 4.3	
3 months post-ablation RVFWLS		−28.3 ± 4.3	
Pre-ablation RV4CLS		−18.9 ± 3.8	
3 months post-ablation RV4CLS		−23.3 ± 3.6	
Post-ablation PVC burden reduction			
PVC burden reduction ≥80%	20 (76.9)		
PVC burden reduction <80%	6 (23.1)		

Abbreviations: ACE, angiotensin-converting enzyme; PVC, premature ventricular contraction; LV-GLS, left ventricular global longitudinal strain; RVFWLS, right ventricular free-wall longitudinal strain; RV4CLS, right ventricular four-chamber longitudinal strain; SD, standard deviation; IQR, interquartile range; QRS, QRS complex. The Holter data required for this calculation were incomplete in three patients; therefore, circadian variability could only be evaluated in 23 of the 26 patients.

Table 2. Association between PVC burden reduction and strain recovery.

Parameter	ΔPVC%	ΔStrain	Spearman r_s	*p*-value
LV-GLS (%)	81.5 ± 25.4	−3.2 ± 2.9	–0.51	0.008
RVFWLS (%)	81.5 ± 25.4	−5.2 ± 5.1	–0.49	0.010
RV4CLS (%)	81.5 ± 25.4	−4.5 ± 4.5	–0.24	0.246

Data are presented as mean ± SD. ΔStrain = 3 months – baseline (negative values indicate improvement). r_s indicates Spearman's rank correlation coefficient. *p* values were calculated using Spearman correlation. Abbreviations: PVC, premature ventricular contraction; LV-GLS, left ventricular global longitudinal strain; RVFWLS, right ventricular free-wall longitudinal strain; RV4CLS, right ventricular four-chamber longitudinal strain.

and RV4CLS values at follow-up. Second, the magnitude of PVC burden reduction correlated with the degree of strain recovery, particularly for RVFWLS (Spearman's r_s = −0.49; p = 0.010) and LV-GLS (Spearman's r_s = −0.51; p = 0.008), while no significant association was identified for RV4CLS. In exploratory multiple regression analyses adjusting for baseline strain and baseline PVC burden, ΔPVC% remained associated with improvement in LV-GLS and RVFWLS, but not RV4CLS, suggesting differential sensitivity of strain parameters to PVC burden reduction. Third, patients achieving ΔPVC% ≥80% exhibited significantly greater improvements in ΔLV-GLS and ΔRVFWLS compared with those with ΔPVC% <80%, while differences in ΔRV4CLS remained non-significant. Taken together, these results showed that greater ectopic burden reduction was consistently associated with measurable mechanical recovery, while emphasizing the multifactorial nature of ventricular functional improvement following PVC ablation [3].

The incremental contribution of this study is the simultaneous assessment of LV and RV deformation after ablation of idiopathic RVOT PVCs. While previous studies have reported LV strain recovery after PVC suppres-

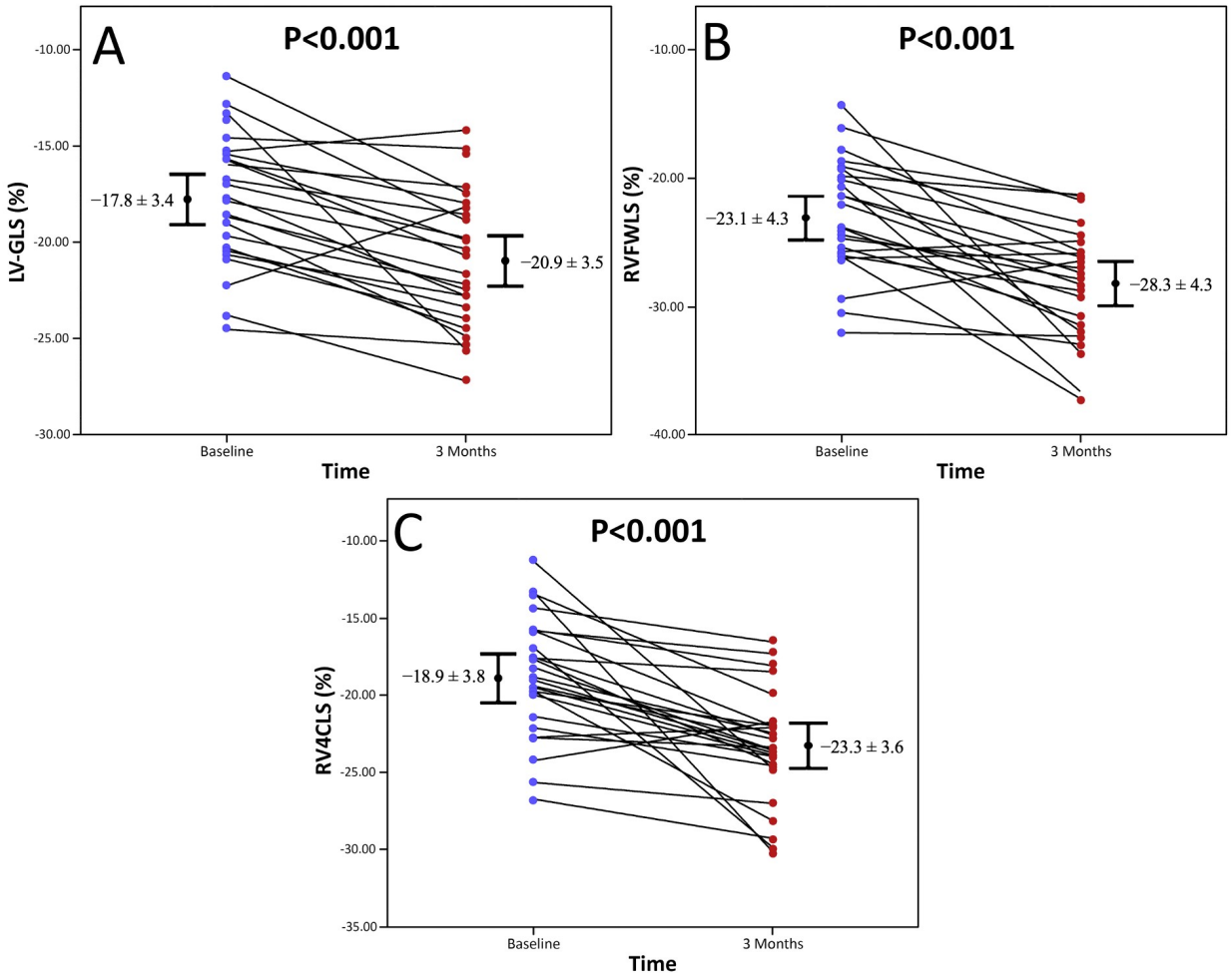

Fig. 1. Pre- and post-changes in biventricular longitudinal strain after right ventricular outflow tract premature ventricular contraction (RVOT PVC) ablation. (A) Left ventricular global longitudinal strain (LV-GLS), (B) right ventricular free-wall longitudinal strain (RVFWLS), and (C) right ventricular 4-chamber longitudinal strain (RV4CLS) measured at baseline and 3 months after catheter ablation of idiopathic RVOT PVCs. Each black line represented an individual patient trajectory, connecting paired baseline and follow-up measurements. Blue dots showed baseline values, and red dots indicated 3-month follow-up values. Black circles with vertical error bars represented group mean ± standard deviation at each time point. More negative strain values indicated better myocardial deformation. All 3 strain parameters demonstrated significant improvement at follow-up (paired analysis, $p < 0.001$). *p*-values were calculated using a paired *t*-test for LV-GLS and a Wilcoxon signed-rank test for RVFWLS and RV4CLS.

Table 3. Comparison by PVC burden reduction threshold (≥80% vs <80%).

Parameter	Groups		*p*-value
	ΔPVC% <80% (n = 6)	ΔPVC% ≥80% (n = 20)	
ΔLV-GLS (%)	−0.7 ± 2.9	−3.9 ± 2.5	0.021
ΔRVFWLS (%)	−1.3 ± 3.3	−6.4 ± 5.0	0.021
ΔRV4CLS (%)	−3.6 ± 2.2	−4.8 ± 4.9	0.692

Data are presented as mean ± SD. Δ = 3 months − baseline (negative values indicate improvement). *p* values were calculated using the Mann–Whitney U test. Abbreviations: PVC, premature ventricular contraction; LV-GLS, left ventricular global longitudinal strain; RVFWLS, right ventricular free-wall longitudinal strain; RV4CLS, right ventricular four-chamber longitudinal strain.

Table 4. Simple and multiple linear regression analyses for strain recovery.

Variables	Simple Linear Regression			Multiple Linear Regression		
	b coefficient	95% CI	*p*-value	b coefficient	95% CI	*p*-value
ΔLV-GLS						
Low circadian variability	−2.496	−5.122 to 0.131	0.061			
Interpolated PVCs	−2.742	−7.222 to 1.738	0.219			
ΔPVC%	−0.049	−0.094 to −0.005	0.032	−0.055	−0.100 to −0.009	0.028
Baseline LV-GLS	−0.319	−0.666 to 0.029	0.071	−0.036	−0.632 to 0.021	0.065
Baseline PVC Burden	0.016	−0.145 to 0.176	0.842	0.104	−0.045 to 0.252	0.163
ΔRVFWLS						
Hypertension	−2.916	−7.159 to 1.327	0.169			
Asymtomatic status	7.492	0.265 to 14.719	0.043			
ΔPVC%	−0.083	−0.160 to −0.006	0.035	−0.072	−0.141 to −0.002	0.044
Baseline RVFWLS	−0.699	−1.097 to −0.301	0.001	−0.663	−1.059 to −0.267	0.002
Baseline PVC Burden	−0.100	−0.370 to 0.171	0.454	0.079	−0.151 to 0.310	0.483
ΔRV4CLS						
Hypertension	−2.425	−6.152 to 1.302	0.192			
Interpolated PVCs	3.946	−2.751 to 10.642	0.236			
ΔPVC%	−0.025	−0.098 to 0.048	0.479	−0.036	−0.098 to 0.026	0.245
Baseline RV4CLS	−0.723	−1.106 to −0.340	0.001	−0.735	−1.124 to −0.346	0.001
Baseline PVC Burden	0.023	−0.217 to 0.262	0.846	0.081	−0.123 to 0.284	0.420

Variables with $p < 0.25$ in simple linear regression and clinical relevance were entered into the multiple linear regression model. b indicates the estimated unstandardized regression coefficient. Abbreviations: CI, confidence interval; PVC, premature ventricular contraction; LV-GLS, left ventricular global longitudinal strain; RVFWLS, right ventricular free-wall longitudinal strain; RV4CLS, right ventricular four-chamber longitudinal strain.

sion, this study extends the results by evaluating RV strain parameters and by considering the concept of ventricular interdependence. Combined assessment of LV-GLS, RVFWLS, and RV4CLS can provide a more integrated view of post-ablation mechanical recovery because RVOT ectopy directly affects RV activation and mechanics while also influencing LV deformation through septal motion and biventricular interaction. RVFWLS was consistently associated with PVC burden reduction, showing that it was more sensitive to ectopic burden suppression, while RV4CLS could be affected by septal contribution and ventricular interdependence.

4.2 Biventricular Subclinical Functional Recovery: Pre-ablation vs 3 Months Post-ablation

The significant improvement in LV-GLS, RVFWLS, and RV4CLS at 3 months emphasized the recovery of longitudinal myocardial mechanics, even among patients with preserved baseline LVEF. Strain imaging, particularly GLS, was known to detect subtle systolic dysfunction earlier than LVEF [11]. Therefore, post-ablation changes in strain precede detectable changes in conventional systolic indices. From a pathophysiological perspective, frequent PVCs could generate repetitive electrical-mechanical dyssynchrony, increase myocardial wall stress, reduce systolic efficiency, and promote adverse remodeling [3]. Suppression of the ectopic focus by catheter ablation reduced this abnormal mechanical burden and facilitated restoration of longitudinal shortening.

These results were consistent with previous evidence and European Society of Cardiology (ESC) guideline recommendations showing the clinically meaningful association between higher PVC burden (often ≥10%) and ventricular dysfunction, and supporting catheter ablation as an effective therapeutic strategy when PVC-mediated myocardial dysfunction is suspected [1,5,6]. In addition, imaging consensus statements such as the American Society of Echocardiography/European Association of Cardiovascular Imagin (ASE/EACVI) recommend the use of strain parameters, particularly LV-GLS and RV strain, given their diagnostic and prognostic value and sensitivity for detecting early functional changes when image quality permits [11]. The consistent improvement observed across LV-GLS, RVFWLS, and RV4CLS in this study supported the potential role of STE as an adjunctive modality for baseline assessment and follow-up modality to evaluate early post-ablation mechanical recovery. Due to the observational pre–post design, causality was not definitively established, and residual confounding could not be excluded.

4.3 Relationship Between PVC Burden Reduction and Strain Improvement

The observed association between PVC burden reduction and strain improvement suggested a graded asso-

ciation, whereby larger reductions in ectopic burden were accompanied by greater recovery in myocardial deformation. This pattern was supported by both correlation analyses and exploratory multiple linear regression models, in which ΔPVC% remained associated with improvement in LV-GLS and RVFWLS after adjustment for baseline strain and baseline PVC burden. The result supports biological plausibility and is consistent with the hypothesis that effective PVC suppression may facilitate subclinical ventricular recovery. Previous evidence in PVC-mediated myocardial dysfunction has similarly shown that higher PVC burden was associated with ventricular dysfunction and remodeling, while substantial burden reduction, particularly to below clinically relevant thresholds (often <10%), was associated with subsequent functional improvement [1,3,5]. However, given the observational pre-post design, this association must not be interpreted as definitive evidence of causality.

The stronger association with ΔRVFWLS was anatomically and physiologically plausible, as RV systolic mechanics were predominantly governed by longitudinal fiber shortening [12]. In this study, ΔRVFWLS demonstrated a consistent association with ΔPVC% in both simple and multiple linear regression analyses, while RV4CLS did not. However, the lack of a significant association between PVC burden reduction and ΔRV4CLS reflected limitations of RV4CLS as a global index. Inclusion of septal segments attenuated RV free-wall–specific recovery due to interventricular dependence and LV-driven septal mechanics, while technical factors (e.g., foreshortening, endocardial border definition, and lower signal-to-noise ratio) could increase measurement variability [13]. These considerations explained why RVFWLS, but not RV4CLS, demonstrated a significant association with ΔPVC% in this study. Overall, these results were consistent with prior evidence showing superior diagnostic and prognostic performance of RVFWLS compared with RV4CLS across several clinical populations [14,15].

Due to the modest sample size, the multiple linear regression analyses must be interpreted as exploratory. The models were deliberately limited to a small number of clinically relevant variables to reduce overfitting, and the results must be viewed as supportive of the correlation and subgroup analyses rather than definitive evidence of independent predictive relationships.

4.4 Comparison of Strain Changes Between PVC Burden Reduction ≥80% and <80% Groups

The greater improvements in ΔLV-GLS and ΔRVFWLS among patients achieving PVC burden reduction ≥80% suggested that the extent of ectopic suppression could be associated with mechanical recovery. This result was consistent with ablation outcome literature, in which sustained procedural success was commonly defined as a ≥80% reduction in PVC burden at follow-up and was associated with greater improvements in ventricular function [16,17]. The lack of a between-group difference in ΔRV4CLS indicated that RV4CLS was less sensitive as an early marker of RV recovery than RVFWLS, potentially due to the inclusion of septal segments and greater influence of LV-driven septal mechanics [13]. However, these subgroup results must be interpreted cautiously, given the small sample size of the ΔPVC% <80% group.

The ≥80% threshold must be interpreted primarily as a standardized study definition rather than an absolute clinical target. Failure to reach ΔPVC% ≥80% at 3 months did not necessarily show clinical failure nor mandate repeat intervention. Instead, management must be guided by symptom burden, serial ambulatory monitoring of PVC burden (e.g., at 6–12 months), optimization of supportive or antiarrhythmic therapy when appropriate, and reassessment for re-ablation in the presence of clinically meaningful arrhythmia burden or evidence of ventricular dysfunction. In this context, strain parameters served as subclinical imaging endpoints to characterize myocardial recovery and provided mechanistic insight, rather than stand-alone determinants for invasive clinical decision-making.

4.5 Clinical Implications

These results suggest that LV-GLS and RVFWLS serve as adjunctive imaging markers for monitoring early subclinical mechanical recovery after catheter ablation in patients with idiopathic RVOT PVCs, particularly in patients with preserved or unchanged LVEF. In patients with a high PVC burden (commonly ≥10%) accompanied by symptoms or evidence of subclinical myocardial dysfunction (reduced LV-GLS and/or RVFWLS), catheter ablation can be considered as part of a strategy to suppress ectopy and potentially mitigate the risk of PVC-mediated cardiomyopathy, consistent with the 2022 ESC guidelines and the Heart Rhythm Society (HRS) 2019 consensus statement [5,18]. However, these results must be interpreted conservatively because this study evaluated surrogate imaging endpoints and did not systematically assess direct clinical outcomes using standardized instruments, such as quantified symptom improvement, arrhythmia recurrence requiring repeat ablation, heart failure events, hospitalization, or mortality. Strain parameters must not be used as stand-alone determinants of clinical management. Clinical decisions must remain primarily guided by symptom burden, Holter-defined PVC burden, and conventional measures of ventricular function. Future larger controlled studies with longer follow-up and clinical endpoints were needed to determine whether strain improvement translates into meaningful clinical benefit.

5. Limitations

This was a single-center study with a modest sample size, which limited generalizability and reduced statistical power for subgroup analyses. The sample size also

limited the stability of multiple linear regression estimates. Although the regression models were restricted to a small number of clinically relevant predictors, residual overfitting and imprecision could not be excluded. Therefore, the adjusted analyses must be interpreted as exploratory and hypothesis-generating. The observational pre-post design without a control group also limited causal inference. The study did not include a control group of patients treated with antiarrhythmic drug therapy alone. Therefore, a direct comparison between catheter ablation and medical therapy could not be performed. Although antiarrhythmic drugs used for PVC suppression were discontinued after ablation and no protocol-driven initiation or intensification of cardiovascular medications was performed during follow-up, the potential influence of background cardiovascular therapy on strain changes cannot be completely excluded.

Follow-up was limited to 3 months, which could not capture late arrhythmia recurrence or longer-term ventricular remodeling. Although symptomatic improvement was reported by all patients who were symptomatic at baseline, symptom status was assessed clinically without a standardized symptom score or quality-of-life instrument. The magnitude of symptomatic benefit could not be quantified. In addition, the study primarily evaluated surrogate imaging endpoints rather than standardized clinical outcomes. PVC burden assessment was based on 24-hour Holter monitoring and could be influenced by day-to-day variability. STE remained dependent on image quality and vendor-specific tracking algorithms. Echocardiographic image acquisition was performed by a single operator, and strain post-processing was conducted by 2 observers. Inter-observer agreement was assessed using ICC. These methodological factors affected measurement reproducibility and must be considered when interpreting the results.

6. Conclusions

In conclusion, in patients with idiopathic RVOT PVCs, catheter ablation is associated with significant improvement in biventricular subclinical function at 3 months, demonstrated by recovery of LV-GLS and RV longitudinal strain indices (RVFWLS and RV4CLS). The magnitude of PVC burden reduction correlates with strain recovery, suggesting a graded association between ectopic suppression and myocardial mechanical improvement. Patients achieving PVC burden reduction ≥80% exhibit greater improvements in LV-GLS and RVFWLS compared with those with <80% reduction. In exploratory multiple linear regression analysis, ΔPVC% remained associated with recovery of LV-GLS and RVFWLS, but not RV4CLS, after adjustment for baseline strain and baseline PVC burden. These strain-based results reflect early subclinical mechanical reverse remodeling after ablation and support the role of STE as an adjunctive follow-up tool. However, given the modest sample size and observational pre-post design, these results must be interpreted as associative and hypothesis-generating. Clinical interpretation must be integrated with symptom status, Holter-defined PVC burden, and conventional ventricular function measures.

Abbreviations

AAD, antiarrhythmic drug; ACE, angiotensin-converting enzyme; ASE, American Society of Echocardiography; CMR, cardiac magnetic resonance; EACVI, European Association of Cardiovascular Imaging; ECG, electrocardiogram; HRS, Heart Rhythm Society; ICC, intraclass correlation coefficients; IQR, Interquartile range; LV, left ventricular; LV-GLS, left ventricular global longitudinal strain; LVEF, left ventricular ejection fraction; PVC, premature ventricular complex; RV, right ventricular; RV4CLS, right ventricular four-chamber longitudinal strain; RVFWLS, right ventricular free-wall longitudinal strain; RVOT, right ventricular outflow tract; SD, standard deviation; SPSS, Statistical Product and Service Solutions (formerly Statistical Package for the Social Sciences); STE, speckle-tracking echocardiography.

Availability of Data and Materials

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

Author Contributions

PA and AY conceptualized and designed the study, coordinated patient recruitment and data collection, performed data management and interpretation, and drafted the manuscript. PA, SH and AYABM provided overall supervision and served as research consultants, contributing to study direction. PA and AYABM supervised the electrophysiology aspects of the study; they also performed the electrophysiology procedures and contributed to interpretation of electrophysiology and procedural outcomes. RPH reviewed the echocardiographic data and performed/validated speckle-tracking strain analysis, contributing to interpretation of imaging findings. HS provided statistical supervision, conducted and validated statistical analyses, and contributed to interpretation of the results. RPH, AYABM, HS, and SH critically reviewed and revised the manuscript for important intellectual content. All authors read and approved the final manuscript. All authors have participated sufficiently in the work and agreed to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

The study was carried out in accordance with the guidelines of the Declaration of Helsinki and was approved by the Health Research Ethics Committee of Dr. Kariadi General Hospital, Semarang, Indonesia (Ethical Approval No. 16480/EC/KEPK-RSDK/2025). Written informed consent was obtained from all individual partici-

pants included in the study prior to the radiofrequency ablation procedure and echocardiographic assessment. Participants were informed that their anonymized clinical data and imaging results would be used for research and publication purposes.

Acknowledgement

Not Applicable.

Funding

This research received no external funding.

Conflicts of Interest

The authors declare no conflicts of interest.

Declaration of AI and AI-Assisted Technologies in the Writing Process

The authors used an artificial intelligence-based language model (QuillBot) to assist with language editing. The authors reviewed and edited and take full responsibility for the content of the manuscript.

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