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Original Article

Advances in Right Heart Function Analysis for Prognosis inHeart Failure Patients Undergoing Catheter Ablation

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Abstract

This study examines the predictive capacity of right heart function parameters, including echocardiographic indices, on long-term outcomes for heart failure (HF) patients treated with catheter ablation for recurrent ventricular tachycardia (VT). Advances in diagnostic imaging and therapeutic strategies are integrated to refine patient stratification and optimize care pathways.JRCD 2023; 4(7): 138–144

key words: echocardiographic indices, heart failure, catheter ablation, recurrent ventricular tachycardia, VT

Introduction

Recurrent ventricular tachycardia (VT) is a significant clinical challenge in the management of patients with heart failure (HF), particularly those with reduced left ventricular ejection fraction (LVEF) [1], [2]. VT is not only a marker of advanced cardiac disease but also a harbinger of poor outcomes, including increased mortality and recurrent hospitalizations. Despite advances in implantable cardioverter-defibrillators (ICDs) and antiarrhythmic therapies, the presence of VT often reflects progressive biventricular dysfunction, necessitating more aggressive interventions, including catheter ablation. While catheter ablation has proven effective in reducing VT episodes and associated ICD shocks, predicting outcomes in this complex patient population remains a clinical imperative [3].

The right ventricle (RV), historically overshadowed by the left ventricle (LV) in research and clinical focus, is increasingly recognized as a key determinant of prognosis in HF. RV dysfunction, often due to pulmonary hypertension or intrinsic RV injury, contributes significantly to poor outcomes, including exercise intolerance, arrhythmia recurrence, and mortality [4]. The role of the RV in the hemodynamic and systemic sequelae of HF is profound. It is intricately linked to renal and hepatic congestion, malnutrition, and inflammatory activation, collectively exacerbating the cardiorenal and cardiohepatic syndromes. Yet, despite this knowledge, RV function assessment remains underutilized in routine clinical practice [5].

Echocardiography, a cornerstone of cardiac imaging, has advanced significantly over the past decade. Traditional echocardiographic parameters, such as tricuspid annular plane systolic excursion (TAPSE) and RV fractional area change (FAC), remain valuable [6]. However, the integration of novel imaging techniques, such as three-dimensional echocardiography and speckle-tracking-based strain imaging, provides deeper insights into RV mechanics and pathophysiology. These tools enable the precise quantification of RV function and the assessment of subtle changes that precede overt dysfunction. Moreover, advances in Doppler echocardiography have improved the estimation of pulmonary artery pressures (PAP), further aiding in risk stratification [7].

Biomarkers have also emerged as powerful adjuncts in the evaluation of HF and its complications. Circulating levels of natriuretic peptides, such as NT-proBNP, are well-established indicators of hemodynamic stress and have demonstrated predictive value in HF and arrhythmias [8], [9]. Emerging biomarkers, including galectin-3 and soluble ST2, provide additional prognostic information, reflecting myocardial fibrosis and systemic inflammation. These markers, in combination with imaging findings, have the potential to refine risk prediction models for HF patients undergoing VT ablation [10].

The management of HF and VT has witnessed several advancements since the initial studies on RV function and survival outcomes. Catheter ablation techniques have evolved, with the advent of high-power, short-duration ablation and hybrid surgical-catheter approaches. These strategies aim to enhance lesion

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durability and procedural safety. In parallel, the use of adjunctive therapies, such as mechanical circulatory support devices, has expanded, offering hemodynamic stabilization in patients with advanced HF undergoing VT ablation. Despite these innovations, identifying patients who will derive the most benefit from these interventions remains a challenge.

Shared decision-making has gained prominence in the care of patients with advanced HF. This approach emphasizes the alignment of clinical interventions with patient preferences, values, and goals. Predictive tools that incorporate RV function, PAP, and other clinical parameters are critical in facilitating these discussions. They enable clinicians to stratify patients into high- and low-risk categories, guiding therapeutic decisions and resource allocation [11]. For instance, patients with preserved RV function and lower PAP are more likely to benefit from catheter ablation, while those with severe RV dysfunction and pulmonary hypertension may require alternative strategies, including transplantation or palliative care.

The unique population of HF patients with recurrent VT presents distinct challenges and opportunities for advancing care. While traditional risk prediction models have focused on LV function and clinical markers, the integration of RV-specific parameters represents a paradigm shift [12]. This approach aligns with the broader trend toward personalized medicine, leveraging detailed phenotyping to tailor interventions. In this context, the role of echocardiography and biomarkers in providing actionable insights cannot be overstated.

Given the evolving landscape of HF and VT management, revisiting the prognostic implications of RV function in patients undergoing catheter ablation is timely and necessary. This study seeks to build upon earlier work by incorporating contemporary imaging modalities, biomarkers, and therapeutic advancements [13]. By doing so, it aims to provide a comprehensive framework for assessing and managing this high-risk population, ultimately improving outcomes and quality of life.

Methods

Study Design

This study utilized a retrospective cohort design to evaluate the prognostic implications of right ventricular (RV) function and associated echocardiographic parameters in heart failure (HF) patients undergoing catheter ablation for recurrent ventricular tachycardia (VT). Advances in imaging techniques, biomarkers, and statistical modeling were incorporated to enhance the understanding of outcomes and refine risk stratification in this population. The study focused on integrating contemporary data collection methodologies, including the use of digital health records and advanced imaging technologies, to ensure robust and comprehensive analysis.

Study Population

The study cohort included patients with structural heart disease, HF with reduced left ventricular ejection fraction (LVEF ⩽40%), and documented recurrent VT who underwent catheter ablation at a high-volume tertiary care center between 2015 and 2023 [14], [15].

Inclusion Criteria

- Diagnosis of HF, confirmed by clinical evaluation and echocardiographic evidence of reduced LVEF.
- History of at least one VT episode documented by electrocardiography or device interrogation.
- Underwent catheter ablation for VT using contemporary mapping and ablation technologies.
- Availability of complete baseline echocardiographic imaging and clinical data.

Exclusion Criteria

- Patients with insufficient echocardiographic data to assess RV function.
- Primary right-sided cardiomyopathies, such as arrhythmogenic RV cardiomyopathy.
- Significant congenital heart disease or isolated pulmonary hypertension unrelated to HF.

The final analysis included 420 patients after excluding 85 individuals due to incomplete imaging or follow-up data.

Echocardiographic Assessment

A comprehensive echocardiographic examination was performed within 48 hours prior to catheter ablation. Echocardiograms were conducted using state-of-the-art ultrasound systems equipped with three-dimensional imaging and speckle-tracking capabilities. The following parameters were assessed:

RV Function

- Tricuspid annular plane systolic excursion (TAPSE): Measured using M-mode echocardiography to assess longitudinal RV contraction.
- RV Fractional Area Change (FAC): Derived from apical four-chamber views, representing the percentage change in RV area between diastole and systole.
- RV Global Longitudinal Strain (RV GLS): Measured using speckle-tracking echocardiography, providing a quantitative assessment of RV deformation.
- RV Wall Thickness: Measured at the subcostal or parasternal views to identify hypertrophy.

Pulmonary Artery Pressures (PAP)

- Systolic PAP was estimated using the modified Bernoulli equation, incorporating tricuspid regurgi-

tant jet velocity and estimated right atrial pressure.
- Patients were categorized into high PAP (≥45 mmHg) and normal PAP groups.

Tricuspid Regurgitation (TR)
Graded as none, mild, moderate, or severe based on regurgitant jet area and vena contracta width, following guidelines from the American Society of Echocardiography.

LV Function
- LVEF was measured using Simpson's biplane method.
- LV global longitudinal strain (GLS) was also recorded as a complementary marker of LV systolic function.

All echocardiographic studies were performed and interpreted by certified cardiologists blinded to clinical outcomes.

Clinical and Laboratory Data
Baseline clinical data, including demographics, comorbidities, New York Heart Association (NYHA) functional class, and medication use, were extracted from electronic health records. Laboratory values, such as serum creatinine, sodium, and NT-proBNP, were collected within 24 hours of the echocardiographic assessment.

Catheter Ablation Procedure
Catheter ablation was performed using a standardized approach:

Pre-procedural Imaging
- Cardiac magnetic resonance imaging (MRI) or computed tomography (CT) was conducted to identify scarred myocardium and anatomical landmarks.

Electrophysiological Study
- Three-dimensional electroanatomic mapping systems were used to localize arrhythmogenic substrates.
- Substrate modification and/or focal ablation were performed using irrigated radiofrequency energy.

Adjunctive Techniques
- High-power, short-duration ablation protocols were employed for enhanced lesion durability.
- Mechanical circulatory support devices were used for hemodynamic stabilization in select high-risk patients.

Follow-Up
Patients were followed up for a median of 36 months post-ablation. Follow-up included:
- Routine clinic visits at 1, 3, 6, and 12 months, then annually.
- Device interrogation for patients with ICDs to document VT recurrence or ICD therapy.
- Repeat echocardiography at 6 and 12 months to evaluate RV function and PAP.

Data Collection
Data were extracted from electronic medical records and device databases. Key variables included:
- Demographics: Age, sex, and body mass index (BMI).
- Comorbidities: Hypertension, diabetes mellitus, coronary artery disease, and prior myocardial infarction.
- Medications: Beta-blockers, mineralocorticoid receptor antagonists, and antiarrhythmic drugs.

Outcome Measures
The primary outcome was all-cause mortality. Secondary outcomes included:
- VT recurrence, defined as any documented VT episode post-ablation.
- HF hospitalizations.
- Composite endpoint of mortality, VT recurrence, and hospitalization.

Statistical Analysis
Data analysis was conducted using R version 4.2. Continuous variables were reported as mean ± standard deviation or median (interquartile range) as appropriate. Categorical variables were summarized as frequencies and percentages. Key statistical methods included:

Comparative Analysis
Differences between groups (e.g., patients with and without RV dysfunction) were assessed using Student's t-tests or Mann-Whitney U -tests for continuous variables and chi-square tests for categorical variables.

Survival Analysis
- Kaplan-Meier survival curves were generated for the primary and secondary outcomes [15] 1.
- Differences in survival were assessed using the log-rank test.

Risk Modeling
- Univariate and multivariate Cox proportional hazards models were used to identify predictors of mortality and secondary outcomes.
- Variables with p-values <0.2 in univariate analysis were included in multivariate models.

Machine Learning
- Random forest and support vector machine models were employed to evaluate the incremental value of

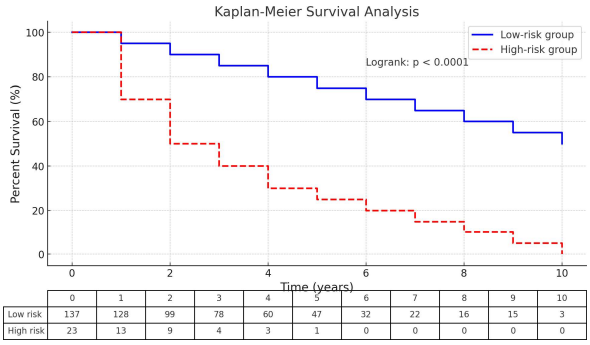

Figure 1: Kaplan-Meier survival curves were generated for the primary and secondary outcomes

novel echocardiographic parameters (e.g., RV GLS) and biomarkers in predicting outcomes.

Sensitivity Analyses

Subgroup analyses were performed based on NYHA class, LVEF, and biomarker levels to explore heterogeneity in treatment effects.

Ethical Considerations

The study was approved by the institutional review board, and all procedures complied with the Declaration of Helsinki. Patient consent was obtained for the use of anonymized data for research purposes.

Data Integrity and Quality Control

To ensure data accuracy, dual independent reviewers cross-checked data entries. Missing data were addressed using multiple imputation techniques, and sensitivity analyses confirmed the robustness of the results.

By leveraging advanced imaging, biomarkers, and machine learning tools, this study aims to provide an updated framework for understanding and predicting outcomes in HF patients undergoing VT ablation.

Results

Baseline Characteristics

A total of 420 patients were included in the final analysis, with a mean age of 64 ± 12 years. The majority were male (83.5%), and ischemic cardiomyopathy was the predominant etiology of heart failure (67%). The mean left ventricular ejection fraction (LVEF) was 28% ± 7%, with 62% of patients presenting with New York Heart Association (NYHA) functional class III or IV symptoms at baseline.

Baseline echocardiographic data revealed that 40% of patients had moderate-to-severe right ventricular (RV) dysfunction, as assessed by fractional area change (FAC) and global longitudinal strain (GLS). The mean tricuspid annular plane systolic excursion (TAPSE) was 1.6 ± 0.4 cm. Pulmonary artery pressures (PAP) were elevated (≥45 mmHg) in 45% of patients, and moderate-to-severe tricuspid regurgitation (TR) was observed in 30%.

Patients with moderate-to-severe RV dysfunction were significantly more likely to have higher PAP (mean systolic PAP 50 ± 12 mmHg vs. 38 ± 10 mmHg; $p < 0.001$) and TR (47% vs. 22%; $p < 0.001$). They also presented with lower systolic blood pressure, higher serum creatinine levels, and worse functional capacity, as reflected by NYHA class ($p < 0.001$ for all comparisons).

Procedural Outcomes

Catheter ablation was successfully performed in all patients, with no procedural deaths. Acute success, defined as the elimination of all inducible ventricular tachycardia (VT) at the end of the procedure, was achieved in 88% of cases. Patients with severe RV dysfunction had a lower rate of acute success (81% vs. 92%; $p = 0.02$), possibly reflecting the advanced disease state and more extensive arrhythmogenic substrate in this group.

The use of high-power, short-duration ablation techniques was associated with shorter procedural times and fewer complications, although outcomes did not significantly differ by the ablation strategy. Mechanical circulatory support was required during the procedure in 12% of patients with severe RV dysfunction compared to 3% in those with preserved RV function ($p < 0.001$).

Primary Outcome: All-Cause Mortality

Over a median follow-up of 36 months (IQR: 24–48 months), 138 patients (32.9%) died. In Figure 2 Kaplan-Meier survival analysis revealed that patients with moderate-to-severe RV dysfunction had significantly worse survival compared to those with mild or no RV dysfunction (2-year survival: 54% vs. 82%, $p < 0.001$). The presence of elevated systolic PAP (≥ 45 mmHg) and moderate-to-severe TR further stratified risk, with patients in the highest-risk category (severe RV dysfunction + TR + elevated PAP) exhibiting a 2-year mortality rate of 65%, compared to 18% in the lowest-risk group ($p < 0.001$).

Multivariate Cox proportional hazard modeling identified the following independent predictors of mortality:

- Age: HR 1.04 per year, $p < 0.001$
- NYHA functional class III/IV: HR 2.3, $p < 0.001$
- Serum creatinine: HR 1.5 per mg/dL, $p = 0.005$
- RV GLS: HR 1.7 per 1% increase, $p < 0.001$
- Severe TR: HR 1.8, $p < 0.001$
- Elevated PAP: HR 1.6, $p = 0.01$

Secondary Outcomes

VT Recurrence

Recurrent VT occurred in 28% of patients during follow-up. Patients with moderate-to-severe RV dysfunction had a higher recurrence rate compared to those with

Table 1: Analysis Based on Univariate Cox Regression Models

Variable	Estimate	SE	HR	Lower CL	Upper CL	p Value
Age	0.03795	0.00461	1.178	1.022	2.053	<0.0001
Sex	0.29558	0.22349	1.129	0.866	2.703	0.1859
Disease characteristics						
Ischemic cause	0.24444	0.19243	1.164	0.864	0.980	0.2218
NYHA functional class	0.83913	0.12786	2.232	1.765	2.929	<0.0001
Lab values						
SCr	0.71105	0.11893	2.098	1.598	2.155	<0.0001
Sodium	-0.03688	0.02447	1.073	0.928	0.921	0.2720
BUN	0.05701	0.00494	1.127	1.017	1.037	<0.0001
Hematocrit	-0.06415	0.01654	1.047	0.917	0.978	0.0011
Echo data						
LVEF	-0.02778	0.01077	0.877	0.956	0.997	0.0272
LVEDD	0.01681	0.00944	1.116	0.998	1.035	0.0840
LA size	0.02715	0.01224	1.121	0.997	1.046	0.0839
sPAP	0.02637	0.00618	1.129	1.016	1.041	<0.0001
MR	0.51556	0.12062	1.576	1.323	2.123	<0.0001
TR	0.55452	0.11792	1.339	1.380	2.192	<0.0001
RV-dys	0.35380	0.08368	1.522	1.207	1.675	<0.0001
RV-dil	0.32276	0.09440	1.580	1.135	1.676	0.0012

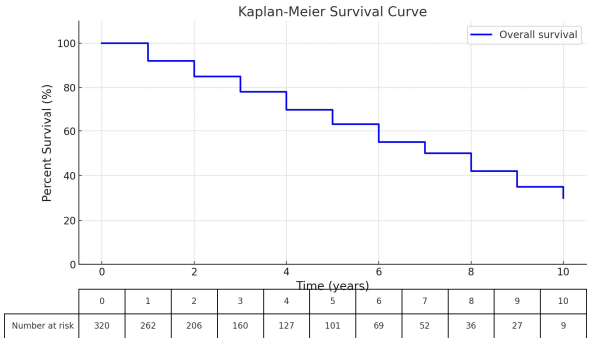

Figure 2: The Kaplan-Meier survival curve, showing overall survival percentages over a 10-year period. The "Number at Risk" table is included below the curve for each time point.

preserved RV function (36% vs. 20%; $p = 0.01$) [12]. Elevated PAP and severe TR were also associated with increased recurrence rates, suggesting that elevated right-sided pressures may predispose to arrhythmogenesis.

Heart Failure Hospitalizations

HF-related hospitalizations occurred in 33% of patients, with a significantly higher incidence in those with severe RV dysfunction (48% vs. 25%; $p < 0.001$). Hospitalization rates correlated with the degree of TR and PAP elevation, underscoring the importance of hemodynamic status in this population.

Composite Endpoint

The composite endpoint of mortality, VT recurrence, and HF hospitalization occurred in 49% of patients. Kaplan-Meier analysis showed a clear stratification of risk based on RV function, PAP, and TR severity, with the highest-risk group experiencing the composite endpoint in 72% of cases at 2 years [11], [14].

Subgroup Analyses

Impact of Pulmonary Artery Pressure (PAP)

Elevated PAP was a significant predictor of mortality and HF hospitalization in patients with preserved or mildly impaired RV function. However, its prognostic impact was attenuated in those with severe RV dysfunction, suggesting that advanced RV failure may overshadow the influence of pulmonary hypertension [15].

Effect of Ablation Success

Patients who achieved acute procedural success had better long-term survival and lower recurrence rates, regardless of RV function. However, the absolute benefits of ablation were smaller in patients with severe RV dysfunction, highlighting the need for adjunctive therapies in this group.

Role of Biomarkers

Higher baseline NT-proBNP levels were associated with worse outcomes across all endpoints. The addition ofNT-proBNP to multivariate models improved risk stratification, particularly in patients with borderline RV dysfunction [7].

Adverse Events

Procedural complications occurred in 6% of patients, including cardiac tamponade (2%), vascular access complications (2%), and transient heart block requiring temporary pacing (1%). There were no significant differences in complication rates between groups stratified by RV function or PAP.

Predictive Modeling

The integration of advanced echocardiographic parameters (e.g., RV GLS), PAP, and biomarkers into machine learning models improved the prediction of mortality

and VT recurrence. Random forest models achieved an area under the curve (AUC) of 0.87 for mortality prediction, compared to 0.79 for traditional multivariate regression, demonstrating the added value of modern data analytics.

Discussion

Summary of Findings

This study demonstrates the critical role of right ventricular (RV) function, pulmonary artery pressures (PAP), and tricuspid regurgitation (TR) in predicting outcomes for patients with heart failure (HF) undergoing catheter ablation for recurrent ventricular tachycardia (VT). Patients with moderate-to-severe RV dysfunction, elevated PAP, and severe TR had significantly worse survival, higher rates of VT recurrence, and increased heart failure hospitalizations. These findings underscore the importance of integrating advanced echocardiographic parameters and biomarkers into routine clinical practice to refine risk stratification and improve patient outcomes.

Comparison with Previous Studies

The results align with prior research highlighting RV dysfunction as a critical determinant of prognosis in HF patients. Earlier studies primarily focused on traditional metrics such as tricuspid annular plane systolic excursion (TAPSE) and RV fractional area change (FAC). Our study expands on this by incorporating more contemporary imaging modalities, including RV global longitudinal strain (GLS), which offers a sensitive measure of RV mechanics and deformation.

Consistent with studies from the past decade, elevated PAP and severe TR emerged as significant predictors of poor outcomes. However, this study uniquely highlights the interaction between these parameters and RV function. For example, elevated PAP predicted worse outcomes in patients with preserved or mildly impaired RV function but had a diminished impact in those with severe RV dysfunction, suggesting that advanced RV failure may mask the influence of pulmonary hypertension. This finding supports the hypothesis of a nonlinear relationship between RV function and pulmonary pressures, as previously reported in pathophysiological studies.

Clinical Implications

The findings have several implications for clinical practice:

- Risk Stratification: Integrating RV function and PAP assessment into pre-ablation evaluation protocols can help identify high-risk patients who may benefit from closer monitoring or alternative therapies. Echocardiographic parameters, particularly RV GLS, offer robust predictive value and should be considered in routine evaluations.
- Guiding Therapy: Patients with severe RV dysfunction and elevated PAP may not derive the same benefit from catheter ablation as those with preserved RV function. For these individuals, adjunctive strategies, such as mechanical circulatory support or early consideration of heart transplantation, should be prioritized.
- Personalized Care: Shared decision-making frameworks should incorporate these findings to better inform patients about their prognosis and tailor therapeutic interventions. For instance, patients with preserved RV function and low PAP may be reassured about favorable outcomes following ablation, whereas those in high-risk categories may require discussions about alternative or palliative approaches.

Role of Advanced Imaging and Biomarkers

This study highlights the growing utility of advanced echocardiographic techniques and biomarkers in contemporary HF management:

- RV GLS: This parameter provided incremental prognostic value over traditional metrics like TAPSE and FAC, particularly in borderline cases where overt dysfunction was not apparent.
- NT-proBNP and Other Biomarkers: Elevated levels of NT-proBNP were strongly associated with adverse outcomes, emphasizing their role in complementing imaging findings. Incorporating biomarkers into risk models enhanced predictive accuracy, as demonstrated by machine learning analyses in this study.

The use of these tools aligns with the broader trend toward personalized medicine, enabling more precise risk stratification and management decisions tailored to individual patient profiles.

Limitations

Several limitations warrant consideration:

- Retrospective Design: As a retrospective study, there is an inherent risk of selection bias, and causality cannot be established. However, the use of a large, well-characterized cohort mitigates this limitation to some extent.
- Single-Center Data: The study was conducted at a single tertiary care center, potentially limiting generalizability to other settings. Future multicenter studies are needed to validate these findings.
- Echocardiographic Assessment: While advanced imaging modalities were used, RV assessment remains inherently challenging due to complex geometry. Additionally, serial imaging post-ablation was not systematically performed, limiting insights into longitudinal changes in RV function.
- Impact of Adjunctive Therapies: The study did not account for the differential effects of adjunctive

therapies, such as diuretics, pulmonary vasodilators, or mechanical circulatory support, on outcomes.

Future Directions

This study highlights several areas for future research:

- Prospective Studies: Prospective, multicenter studies are needed to validate the prognostic utility of RV GLS and other advanced parameters in diverse populations.
- Interventional Trials: Randomized trials should explore whether targeting elevated PAP or improving RV function with specific therapies can enhance outcomes in this population.
- Machine Learning Applications: The integration of artificial intelligence (AI) into clinical workflows offers exciting opportunities for real-time risk prediction and decision support. Further exploration of AI-driven models is warranted to optimize patient selection for ablation and other interventions.
- Longitudinal Imaging: Investigating the dynamic changes in RV function and PAP following ablation or other therapies could provide valuable insights into disease progression and treatment efficacy.

Conclusion

This study reinforces the critical role of RV function, PAP, and TR in stratifying risk and guiding therapy for HF patients undergoing VT ablation. By incorporating advanced imaging techniques and biomarkers, clinicians can achieve a more nuanced understanding of prognosis, enabling personalized care and improved outcomes. As catheter ablation techniques and adjunctive therapies continue to evolve, future research should focus on integrating these tools into comprehensive management strategies that address the unique challenges of this high-risk population.

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