

Comparative Clinical Outcomes of Left Bundle Branch Area Pacing versus Right Ventricular Pacing in Patients with Preserved Ejection Fraction: A 3-Year Follow-Up Study

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Abstract

Purpose

Chronic right ventricular pacing (RVP) can exacerbate heart failure, but the clinical impact of left bundle branch area pacing (LBBAP) in patients with preserved left ventricular ejection fraction (LVEF) remains unclear. This study compared clinical outcomes between LBBAP and RVP in this patient population.

Methods

This prospective registry enrolled *de novo* patients with preserved LVEF (> 50%) and an expected ventricular pacing burden > 20% who underwent transvenous permanent pacemaker implantation between 2020 and 2023. LBBAP was performed using stylet-driven leads (Tendril MRI, Abbott). The composite outcome comprised all-cause mortality, heart failure hospitalization (HHF), pacing-induced cardiomyopathy (PICM), and upgrade to biventricular pacing.

Results

Overall, 242 patients were classified into RVP (n = 125) and LBBAP (n = 117) groups. Baseline characteristics were balanced. Compared with LBBAP, the RVP group had a significantly longer paced QRS duration (pQRSd) (157.5 ± 17.7 ms vs. 129.1 ± 18.0 ms; $p < 0.001$) and lower global longitudinal strain (GLS) ($-15.3 \pm 3.6\%$ vs. $-17.6 \pm 3.5\%$; $p < 0.001$). Over a median 3-year follow-up, the composite outcome was significantly higher in the RVP group than in the LBBAP group (22.4% vs. 9.2%; $p = 0.003$). In multivariate analysis, reduced post-implant GLS (HR 1.361; 95% CI, 1.009–1.834; $p = 0.043$), and pQRSd (HR 1.124; 95% CI, 1.057–1.196; $p < 0.001$) were independent predictors of PICM.

Conclusions

In patients with preserved LVEF and a high pacing burden, LBBAP using standard stylet-driven leads is safe, effective, and associated with better clinical outcomes than RVP, showing close associations with a narrower paced QRS duration and better-preserved post-implant GLS.

1. Introduction

Right ventricular pacing (RVP) has been the standard of care for decades in patients requiring permanent pacemaker (PPM) implantation [1]. However, chronic RVP induces non-physiological ventricular activation, leading to electrical and mechanical dyssynchrony [2, 3]. This dyssynchrony is well known to cause deleterious left ventricular (LV) remodeling and subsequent LV dysfunction, a phenomenon termed pacing-induced cardiomyopathy (PICM) [4], which further increases the risks of atrial fibrillation and heart failure hospitalization. While the detrimental effects of RVP are well-

established in patients with impaired LVEF and a high pacing burden, recent evidence highlights that it also poses a significant concern in patients with preserved EF if they require a high ventricular pacing burden (> 20%).

The use of biventricular pacing (BVP) is well accepted for the treatment of heart failure patients with reduced LVEF and a prolonged QRS duration, with numerous clinical trials performed over the past 20 years demonstrating improvements in morbidity and mortality [5]. However, accumulating evidence suggests that routine BVP implantation in patients likely to experience a high burden of RV pacing has not become a standard of care unless these patients have pre-existing LV dysfunction [6–8].

Recently, left bundle branch area pacing (LBBAP) has gained widespread popularity as a feasible and stable physiological pacing strategy [9]. LBBAP provides low and stable capture thresholds, high R-wave amplitudes, and a shorter learning curve while achieving near-physiological ventricular activation [10, 11]. Although the clinical efficacy and safety of LBBAP have been increasingly reported, the majority of these data have been derived from lumenless leads (LLLs). Consequently, real-world evidence directly evaluating the clinical outcomes of stylet-driven lead (SDL)-based LBBAP—particularly in comparison with RVP for patients with preserved LVEF—remains substantially limited. Therefore, this study aimed to compare clinical outcomes between LBBAP using SDL and conventional RVP within a prospective registry of patients with preserved LVEF and a high ventricular pacing burden.

2. Methods

2.1 Study population

This study was a prospective, observational registry conducted at Chosun University Hospital (Gwangju, South Korea). We enrolled *de novo* patients with a preserved left ventricular ejection fraction (defined as LVEF $\geq$ 50%) who underwent transvenous pacemaker implantation between 2020 and 2023, and had an expected ventricular pacing burden greater than 20%. The exclusion criteria were pre-existing severe valvular heart disease, congenital heart disease, persistent tachyarrhythmia, or a life expectancy of less than one year. Detailed clinical histories and physical examinations were recorded at baseline. Patient demographics, 12-lead electrocardiograms (ECGs), and laboratory data were comprehensively evaluated. The study protocol was approved by the Institutional Review Board of Chosun University Hospital (IRB No. CHOSUN 2024-11-004), and written informed consent was obtained from all patients in accordance with the Declaration of Helsinki.

2.2 Pacemaker implantation

All procedures were performed using standard transvenous implantation techniques via a left pectoral approach, with leads inserted through the axillary vein. In the RVP group, the ventricular lead was positioned in the right ventricular apex or mid-septum based on the operator's discretion. In the LBBAP group, a standard stylet-driven lead with an extendable helix (2088TC-58, Tendril STS, Abbott, Saint Paul,

MN, USA) was delivered using an electrode-incorporated steerable catheter (Agilis HisPro™; Abbott, IL, USA). LBBAP is included left bundle branch pacing (LBBP) and left ventricular septal pacing (LVSP) [12].

Paced QRS morphology and unipolar impedance were continuously monitored throughout the procedure. A 12-lead ECG and intracardiac electrograms were recorded in real time using an electrophysiology system (Prucka CardioLab; GE Healthcare, Waukesha, WI, USA). The implantation technique followed established LBBAP protocols [13–17]. The delivery sheath was introduced into the right ventricle (RV) and positioned adjacent to the right side of the interventricular septum. The optimal LBBAP site was located 1–1.5 cm distal to the His-bundle signal, where sheath pacing demonstrated a 'W' pattern with a notch at the nadir of the QRS complex in lead V1. The lead was then advanced transseptally from the RV septum into the left subendocardial area by rotating it clockwise in increments of 3–4 turns to achieve deep septal engagement. Lead depth was monitored using the current of injury amplitude and sheath angiography to ensure progressive leftward displacement [18].

As the pacing lead approached the left ventricular (LV) endocardial site, successful LBB capture was confirmed by the following criteria: a transition of the QRS notch to the terminal portion forming a typical right bundle branch block (RBBB) 'r' or 'R' pattern in lead V1, a shortened peak LV activation time (pLVAT) < 75 ms in lead V6, and a V6–V1 interval > 44 ms [19–21]. If LBB capture criteria were not met but a terminal R/r' in lead V1 was present, it was defined as LV septal pacing [12].

2.3 Clinical and pacemaker follow-up

Within 24 hours post-implantation, baseline ECG parameters were acquired closest to the PPM implantation. All patients were routinely evaluated as outpatients at 1, 3, 6, and 12 months after implantation, and every 6 to 12 months thereafter. At each follow-up visit, pacemaker interrogation was performed to record the ventricular pacing percentage (VP%), pacing thresholds, sensing parameters, and lead impedance. During these follow-up periods, procedural and post-operative complications were systematically evaluated. Acute ventricular lead-related complications were defined as a composite of lead fracture during implantation or severe right ventricular lead-induced tricuspid regurgitation requiring lead removal. Pocket-related complications comprised pocket or lead infections, or the occurrence of a pocket hematoma requiring additional surgical intervention. For chronic complications, the need for ventricular lead revision following discharge from the index hospitalization was comprehensively assessed. To ensure a comparable follow-up duration between the two groups and mitigate potential chronological confounding bias, the clinical follow-up period for time-to-event analyses was censored at a maximum of 3 years (1,095 days) post-implantation.

2.4 Echocardiography

All patients underwent comprehensive echocardiographic evaluation within seven days of PPM implantation and at the 1-year follow-up using a standard ultrasound system with a 2.5-MHz phased-array transducer (Vivid 9; GE Vingmed, Horten, Norway). Standard M-mode, two-dimensional, and Doppler measurements were obtained following the American Society of Echocardiography guidelines. The LVEF was measured using the modified Simpson's biplane method, and the LV stroke volume was

calculated. Mitral inflow was assessed in the apical four-chamber view using pulsed-wave Doppler ultrasonography. Diastolic function was evaluated using tissue Doppler imaging based on mitral flow velocities, mitral annular septal e' velocity (< 7 cm/s), E/e' ratio (> 14), peak tricuspid regurgitant jet velocity (> 2.8 m/s), and left atrial volume index (LAVI > 34 mL/m²). Diastolic dysfunction was judged to be present if more than half of these available parameters met the predefined cutoff values. Baseline and follow-up examinations were performed using the same machine and analyzed by two experienced echocardiographers blinded to the clinical data.

Global longitudinal strain (GLS) was analyzed using commercially available software (EchoPAC PC Version 113, GE Vingmed Ultrasound). For deformation analysis, endocardial borders were traced on the end-systolic frame in three apical views, with end-systole defined by the QRS complex or the smallest LV volume. The software automatically tracked speckles along the endocardial border throughout the cardiac cycle to compute the peak longitudinal strain, generating an average global value.

2.5 Composite clinical outcomes

The primary composite clinical outcomes comprised all-cause mortality, heart failure hospitalization (HHF), pacing-induced cardiomyopathy (PICM), and upgrade to biventricular pacing (BVP) during the follow-up period. HHF was defined as an unplanned hospital or emergency department visit due to heart failure symptoms requiring the administration of intravenous diuretics [22]. PICM was defined as a $> 10\%$ decrease in LVEF, resulting in a follow-up LVEF of $< 50\%$, as previously reported [23]. An upgrade to BVP was defined as the conversion of the existing pacemaker to a BVP device when the patient met established clinical criteria.

2.6 Statistical analysis

Baseline characteristics are summarized as mean $\pm$ standard deviation for continuous variables, and as frequencies with percentages for categorical variables. Comparisons between the two groups were analyzed using Student's t-test or the Mann–Whitney U test for continuous variables, and the Chi-squared test or Fisher's exact test for categorical variables, as appropriate. Kaplan–Meier survival curves were used to analyze time-to-event data and compared using the log-rank test. A Cox proportional hazards regression model was utilized to determine the independent predictors of PICM. Receiver operating characteristic (ROC) curves were plotted to identify optimal cutoff values using the area under the curve (AUC). All statistical tests were two-sided, and analysis was performed using IBM SPSS Statistics (v. 30.0; IBM Corp., Armonk, NY, USA). P-values < 0.05 were considered statistically significant, and results are presented as hazard ratios (HRs) with 95% confidence intervals (CIs).

3. Results

3.1 Study population

The patient flow diagram for this study is presented in Fig. 1. A total of 523 patients were initially screened from the Chosun Registry between 2020 and 2023. After excluding 114 patients with sick sinus

syndrome and applying strict clinical criteria—including the exclusion of patients with a ventricular pacing rate < 20%, baseline LVEF < 50%, severe valvular disease, baseline battery exchange, or those lost to follow-up—a final cohort of 242 patients with preserved ejection fraction and a high expected ventricular pacing burden was analyzed. The study population was divided into the conventional RVP group (n = 125) and the LBBAP group (n = 117). The baseline demographics and clinical characteristics were well-balanced between the two groups (Table 1). There were no statistically significant differences between the RVP and LBBAP groups regarding age or sex distribution. Similarly, comorbidities, including hypertension, diabetes mellitus, hyperlipidemia, coronary artery disease, and atrial fibrillation, were comparable between the two cohorts.

Table 1
Baseline Characteristics

Age (years)	RVP (N = 125)	LBBAP (N = 117)	P value
	74.86 ± 10.68	77.3 ± 9.73	0.062
Male gender (n, %)	56 (44.8%)	54 (46.2%)	0.833
Cardiovascular risk factor			
Hypertension	87 (70.2%)	86 (73.5%)	0.631
Diabetes Mellites	33 (26.6%)	44 (37.6%)	0.067
Hyperlipidemia	50 (40.3%)	60 (51.3%)	0.088
Coronary artery disease	18 (14.5%)	16 (13.7%)	0.851
Cerebrovascular disorder	18 (14.5%)	21 (17.9%)	0.470
Atrial fibrillation	15 (12.1%)	15 (12.8%)	0.865
2D - Echocardiography			
Ejection Fraction	55.4 ± 7.8	55.8 ± 9.4	0.356
E/E'	13.8 ± 5.3	12.8 ± 4.91	0.136
E (Septal)'	3.08 ± 3.51	5.04 ± 1.74	0.253
TR velocity	2.67 ± 0.44	2.62 ± 0.36	0.298
LAVI	34.4 ± 8.8	33.5 ± 12.4	0.653
GLS	-15.3 ± 3.64	-17.6 ± 3.48	< 0.001
GLS, global longitudinal strain; LAVI, left atrial volume index; LBBAP, left bundle branch area pacing; RVP, right ventricular pacing; TR, Tricuspid regurgitation.			

2D-echocardiography showed that the left ventricular ejection fraction was similar between the groups (55.4 ± 7.8% vs. 55.8 ± 9.4%; p = 0.356). Other conventional parameters, including the E/e' ratio, tricuspid

regurgitation (TR) velocity, and left atrial volume index (LAVI), were also comparable. However, global longitudinal strain (GLS) was significantly better preserved in the LBBAP group than in the RVP group ($-17.6 \pm 3.5\%$ vs. $-15.3 \pm 3.6\%$; $p < 0.001$).

3.2 Electrocardiographic and Device-Related Parameters

Device-related parameters at the time of implantation, including atrial and ventricular lead pacing thresholds, sensing amplitudes (P-wave and R-wave), and electrical impedances, did not differ significantly between the two groups (Table 2). The mean ventricular pacing percentage was high and remarkably similar in both arms ($94.1 \pm 14.6\%$ in the RVP group vs. $93.1 \pm 13.7\%$ in the LBBAP group; $p = 0.714$), confirming a significant burden of chronic ventricular pacing. Notably, the post-implantation paced QRS duration (pQRSd) was significantly narrower in the LBBAP group than in the RVP group (129.1 ± 18.0 ms vs. 157.5 ± 17.7 ms; $p < 0.001$), demonstrating superior electrical synchrony achieved by conduction system pacing. Within the LBBAP group, 103 patients (88.1%) achieved successful left bundle branch pacing, whereas 14 patients (11.9%) presented with left ventricular septal pacing. Regarding device-related complications during the follow-up period, lead-related revisions were required in only two patients: one patient in the RVP group underwent ventricular lead revision due to cardiac perforation, and one patient in the LBBAP group required revision due to acute lead micro-dislodgement. No other major lead- or pocket-related complications were observed in either cohort.

Table 2
Device related parameters

Atrial leads	RVP (N = 125)	LBBAP (N = 117)	P value
Implant P wave	2.92 ± 1.24	2.74 ± 1.20	0.262
Pacing threshold	0.72 ± 0.24	0.75 ± 0.30	0.712
Impedance	479.2 ± 104.72	493.0 ± 114.9	0.356
Ventricular leads			
Implant R wave	10.11 ± 2.49	9.97 ± 2.48	0.714
Pacing threshold	0.71 ± 0.26	0.75 ± 0.28	0.215
Impedance	602.1 ± 107.9	607.1 ± 105.3	0.716
Ventricular pacing percentage (%)	94.1 ± 14.6	93.1 ± 13.7	0.714
Paced QRS duration	157.5 ± 17.7	129.1 ± 18.0	0.001
LBBAP, left bundle branch area pacing; RVP, right ventricular pacing.			

3.3 Composite Clinical Outcomes

The composite clinical outcomes are listed in Table 3. To evaluate long-term outcomes under an equal observation window, the follow-up period was restricted to 3 years. Consequently, the median follow-up duration for the analyzed cohort was 1,095 days (interquartile range [IQR], 1,063–1,095 days). During this period, the primary composite outcome occurred in 33 patients (26.4%) in the RVP group and 12 patients (10.3%) in the LBBAP group, demonstrating a statistically significant clinical benefit favoring LBBAP ($p = 0.003$) (Fig. 2).

Table 3
Composite clinical outcomes.

Composite Outcomes	RVP (N = 125)	LBBAP (N = 117)	P value
	33 (26.4%)	12 (9.4%)	0.003
All-cause mortality, n (%)	20 (16.0%)	10 (8.5%)	0.096
Heart Failure Hospitalization, n (%)	9 (7.2%)	1 (0.9%)	0.016
Pacing induced Cardiomyopathy, n (%)	11 (8.8%)	2 (1.8%)	0.016
Biventricular pacing upgrade, n (%)	4 (3.2%)	0 (0%)	0.050
LBBAP, left bundle branch area pacing; RVP, right ventricular pacing			

When analyzing individual components of the composite endpoint, all-cause mortality showed a numerical but not statistically significant trend toward a reduction in the LBBAP group (16.0% vs. 8.5%; $p = 0.096$). The incidence of PICM was markedly higher in the RVP group than in the LBBAP group (8.8% [$n = 11$] vs. 1.7% [$n = 2$]; $p = 0.016$). Similarly, heart failure hospitalizations (HHF) occurred in 9 patients (7.2%) in the RVP group compared to 1 patient (0.9%) in the LBBAP group ($p = 0.016$). Notably, all cases of HHF and PICM within the LBBAP group were observed in patients who had undergone LVSP. Upgrades to BVP due to clinical worsening were required in 4 patients (3.2%) in the RVP group, whereas no patients in the LBBAP group required an upgrade (0.0%; $p = 0.050$).

Cox proportional hazards regression analysis was applied to identify the predictors of PICM (Table 4). Reduced post-implant GLS (HR, 1.361; 95% CI, 1.009–1.834; $p = 0.043$) and prolonged pQRSd (HR, 1.124; 95% CI, 1.057–1.196; $p < 0.001$) were independent predictors of PICM.

Table 4
Predictors of pacing induced cardiomyopathy using Multivariate Analysis

	Univariate analysis			Multivariate analysis		
	HR	95% CI	P value	HR	95% CI	P value
Age	1.049	1.011–1.089	0.052			
Gender (Male)	0.662	0.223–1.971	0.459			
LBBAP	0.190	0.042–0.857	0.031			
Ejection Fraction	0.911	0.859–0.966	0.002			
Diastolic dysfunction	1.942	1.159–3.255	0.012			
GLS	1.542	1.308–1.817	0.001	1.361	1.009–1.834	0.043
Paced QRS duration	1.119	1.069–1.170	0.001	1.124	1.057–1.196	0.001
GLS, global longitudinal strain; LBBAP, left bundle branch area pacing.						

The ROC curve analysis demonstrated an AUC of 0.918 (95% CI, 0.865–0.971; $p = 0.001$) for pQRSd, indicating that a pQRSd cutoff of 163 ms had an 82.3% sensitivity and an 81.6% specificity for predicting the incidence of PICM (Fig. 3). Additionally, it revealed an AUC of 0.897 (95% CI, 0.847–0.948; $p < 0.001$) for GLS, indicating that a GLS cutoff value of -14.3% had a 100% sensitivity and a 76.2% specificity for predicting the development of PICM.

4. Discussion

The principal finding of our study was that in patients with preserved LVEF and a high expected ventricular pacing burden, LBBAP was associated with better composite clinical outcomes compared with conventional RVP over a 3-year clinical follow-up period. Furthermore, we demonstrated that real-world LBBAP using standard stylet-driven leads (SDLs) can be performed safely and effectively with low complication rates. LBBAP was associated with a significantly narrower pQRSd and better preserved post-implant GLS, which subsequently translated into a marked reduction in the incidence of PICM.

Since the inception of cardiac pacing in 1958, right ventricular pacing remains the established site for permanent pacemaker lead placement [1]. Although RVP effectively treats bradyarrhythmias, its non-physiological electrical propagation bypasses the native His-Purkinje system, inherently inducing electrical and mechanical dyssynchrony. This dyssynchrony triggers asymmetrical hypertrophy, localized myofibrillar disarray, and progressive LV remodeling, which may ultimately culminate in PICM and heart failure [2–4]. The clinical impact of PICM is profound, significantly elevating the risks of atrial fibrillation, HHF, and cardiac mortality. Consequently, minimizing the detrimental effects of chronic ventricular dyssynchrony has become a paramount clinical priority, particularly in patients presenting with a high ventricular pacing burden.

To mitigate the drawbacks of chronic RVP, BVP was introduced and has become the established standard of care for heart failure patients with reduced LVEF and a prolonged QRS duration, with landmark trials such as BLOCK-HF, HOBIPACE, and COMBAT demonstrating substantial improvements in morbidity and mortality [5, 24, 25]. However, the clinical efficacy of BVP does not readily translate to patients with preserved LVEF. The PACE trial revealed that while BVP prevented adverse LV remodeling compared with RVP in patients with normal LVEF, it provided no significant advantages in functional parameters or HHF [6]. Similarly, the BioPACE trial yielded conflicting results regarding the benefit of BVP in patients with relatively preserved LVEF (> 40%), demonstrating no mortality benefit and uncertain longitudinal effects on hospitalization [7, 8]. Reflecting these mixed clinical trial outcomes, current guidelines offer cautious recommendations for BVP only in patients with a mid-range LVEF (36–50%) who require a high pacing burden, whereas routine BVP implantation remains non-standard and unproven for patients with an LVEF > 50% [26]. Consequently, a definitive therapeutic gap persists for patients with preserved LVEF and a high ventricular pacing burden.

Conduction system pacing (CSP), which includes His bundle pacing (HBP) and LBBAP, holds great promise to bridge this therapeutic gap by preserving physiological ventricular activation and preventing PICM. In clinical investigations, upfront HBP implantation was associated with a notable decrease in the composite endpoint of death, HHF, or the need for an upgrade to BVP compared with standard RVP [27]. Nevertheless, the widespread clinical adoption of HBP has been substantially hindered by its inherent technical and performance limitations. These include elevated and unstable pacing thresholds, potential sensing challenges such as atrial or far-field oversensing, and subsequent complexities in long-term device programming. These persistent procedural challenges have directly paved the way for LBBAP to emerge as a more feasible, stable, and anatomically favorable physiological pacing modality.

Recently, the clinical evidence for LBBAP has been further strengthened by the large-scale European multicenter registry (MELOS study), which demonstrated high procedural success (92.4%) and favorable safety profiles [21]. Furthermore, the recently published MELOS Reloaded study, which evaluated 3,382 propensity-matched patients with preserved or mildly reduced LVEF (> 40%) and high ventricular pacing burdens (> 20%), provided data showing that routine LBBAP is associated with a lower long-term all-cause mortality (HR, 0.53; 95% CI, 0.42–0.65; $p < 0.001$) and a dramatic reduction in heart failure hospitalizations compared with RVP [28]. Interestingly, while the MELOS Reloaded study demonstrated a significant survival benefit, our study observed a substantial numerical reduction in all-cause mortality that did not reach statistical significance (16.0% vs. 8.5%; $p = 0.096$). This discrepancy is likely due to our cohort being underpowered to detect a statistically significant difference in all-cause mortality over a 3-year clinical follow-up period. Nonetheless, our registry robustly confirms that LBBAP significantly mitigates the incidence of the primary composite outcome, driven predominantly by a marked reduction in HHF and PICM.

Most procedural experience with LBBAP globally has been accumulated using lumenless leads (LLs) rather than stylet-driven leads (SDLs). Consequently, literature directly comparing clinical outcomes of SDL-based LBBAP versus RVP remains scarce. By demonstrating the feasibility, safety, and clinical

efficacy of LBBAP performed exclusively with SDLs (Tendril MRI, Abbott), our study provides a unique and highly practical contribution to real-world evidence, demonstrating that excellent clinical outcomes are achievable using standard, widely available hardware.

Accumulating evidence suggests that LVSP may not fully resolve electromechanical dyssynchrony compared with true LBBP. Crucially, in our study, all cases of HHF and PICM observed within the LBBAP group occurred exclusively in patients who received LVSP, whereas no clinical events occurred in those with successful LBBP. This clinical divergence underscores that the ultimate prognosis of conduction system pacing is determined by the quality of electromechanical resynchronization, which is directly reflected by post-procedural pQRSd and early post-implant GLS preservation. Consequently, rather than viewing LBBAP as a uniform procedural entity, meticulous optimization of the lead position to capture the true conduction system, thereby minimizing pQRSd and preserving early post-implant GLS, is paramount to effectively halting heart failure progression.

In our study, prolonged pQRSd and reduced post-implant GLS were identified as the important risk factors for the development of PICM in patients with preserved LV function. RVP results in a left ventricular electrical activation sequence resembling left bundle branch block (LBBB) morphology. The resulting electrical dyssynchrony is manifest as a prolonged QRS duration due to low myocardial conduction. Thus, prolonged pQRSd is a well-known risk factor for PICM, indicating that patients with prolonged pQRSd are at substantially higher risk of developing subsequent ventricular deterioration [29–32]. Khurshid et al. proposed that a pQRSd of 150 ms was a sensitive indicator of pacemaker-induced heart failure [30]. Furthermore, their study showed that a pQRSd of 160 ms had an 88.0% sensitivity and a 44.0% specificity for predicting PICM, yielding an AUC of 0.656. In comparison, our ROC analysis revealed that a pQRSd cutoff of 163 ms provided a remarkably higher predictive power, demonstrating a sensitivity of 82.3% and a specificity of 81.6%, with an impressive AUC of 0.918. Importantly, our multivariate analysis confirmed that prolonged pQRSd is a powerful independent risk factor for the development of PICM. Because conventional RVP inherently broadens the QRS complex, it chronically elevates the mechanical workload of the lateral wall, accelerating ventricular deterioration even in patients who start with a normal ejection fraction. By maintaining a narrow paced QRS, LBBP preserves mechanical intraventricular synchrony and directly protects patients against heart failure deterioration, which is consistent with the clinical findings of our registry.

In our multivariate model, post-implant GLS was another independent predictor of PICM. Myocardial strain is an emerging parameter used to assess the systolic function of cardiac chambers in a more elaborate manner. The most evaluated strain parameter is GLS, which is more sensitive than LVEF, and can be used to identify subclinical LV dysfunction [33]. Building on our previous finding that RVP impairs myocardial deformation after PPM implantation [34], the present study confirms that this early post-implant GLS degradation—captured as early as one week—serves as a powerful predictor of long-term PICM, even in patients with a preserved EF. In our cohort, the optimal GLS cutoff value for predicting PICM was -14.3% , which yielded a sensitivity of 100% and a specificity of 76.2%. These findings indicate that even among patients presenting with preserved LV function, a substantial reduction in subclinical LV

function can occur after RV pacing, as unmasked by an impaired post-implant GLS. Hence, early post-implant GLS monitoring represents an effective surrogate marker for risk stratification, wherein LBBAP may serve as a preferred pacing modality over RVP to prevent long-term adverse remodeling.

4.1 Limitations

Despite the promising results, this study has several limitations that should be acknowledged. First, this was a single-center prospective registry, which may limit the generalizability of the findings to other clinical settings. Second, despite the prospective design of data collection, the selection of the pacing modality was left to the discretion of the attending operators, which introduces potential selection bias. Third, the sample size was relatively small ($n = 242$); thus, the statistical power may have been insufficient to detect significant differences in individual hard clinical endpoints, such as all-cause mortality, despite the clear divergence observed in the primary composite outcome. Larger, multicenter randomized trials are warranted to confirm these findings across broader populations. Fourth, our findings are subject to device-specific considerations, as this study exclusively utilized hardware from a single manufacturer (Tendril MRI lead, Abbott). Consequently, the applicability of these results to other commercially available devices with distinct lead designs or pacing algorithms remains to be validated. Despite these limitations, our study provides valuable real-world evidence that in patients with preserved LVEF and a high expected ventricular pacing burden, LBBAP using stylet-driven leads is both feasible and safe, offering significantly better clinical outcomes compared with conventional RVP.

5. Conclusions

This study demonstrated that in patients with preserved LVEF and a high pacing burden, LBBAP using stylet-driven leads is safe, effective, and associated with better clinical outcomes. LBBAP is associated with a narrower paced QRS duration and favorable post-implant GLS, which subsequently mitigates the long-term risk of pacing-induced cardiomyopathy.

Declarations

Conflict of interest

The authors declare that there is no conflict of interest.

Author Contribution

Conceptualization: Jeong HK, Kim SS; Data curation: Jeong HK, Kim SS; Formal analysis: Jeong HK, Kim SS; Funding acquisition: Kim SS; Investigation: Jeong HK, Kim SS; Methodology: Jeong HK, Kim SS; Project administration: Jeong HK, Kim SS; Resources: Jeong HK, Kim SS; Software: Jeong HK, Kim SS; Supervision: Jeong HK, Kim SS, Kim HK, Ki YJ, Choi DH, Park KH; Validation: Jeong HK, Kim SS, Kim HK,

Ki YJ, Choi DH, Park KH; Visualization: Jeong HK, Kim SS, Kim HK, Ki YJ, Choi DH, Park KH; Writing - original draft: Kim SS; Writing - review & editing: Jeong HK, Kim SS.

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Figures

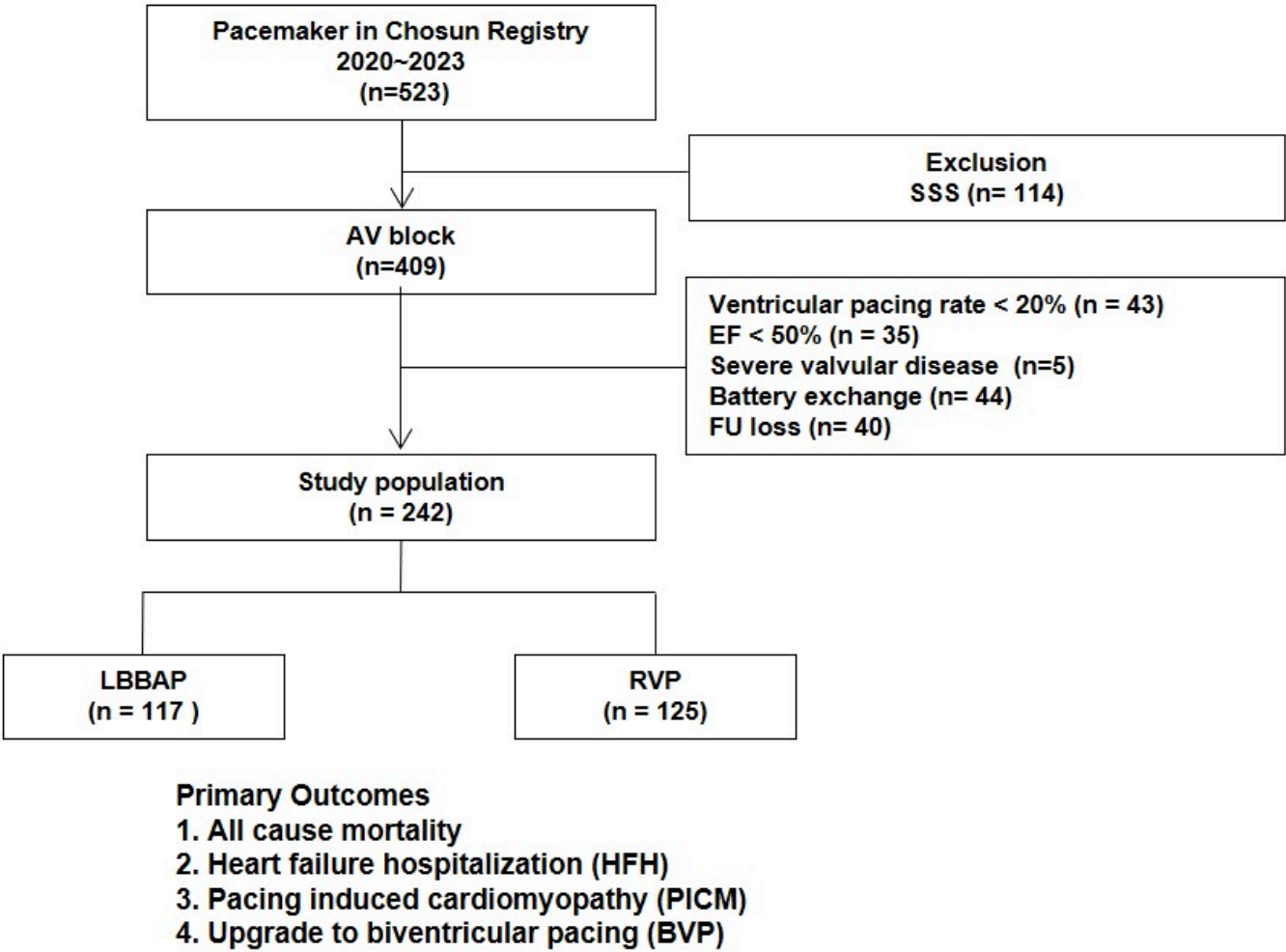


Figure 1

Study Enrollment flow chart. Flow chart illustrating patient selection, exclusion criteria, and final cohort stratification into LBBAP (n = 117) and RVP (n = 125) groups. AV, atrioventricular; FU, follow-up; LBBAP, left bundle branch area pacing; RVP, right ventricular pacing; SSS, sick sinus syndrome.

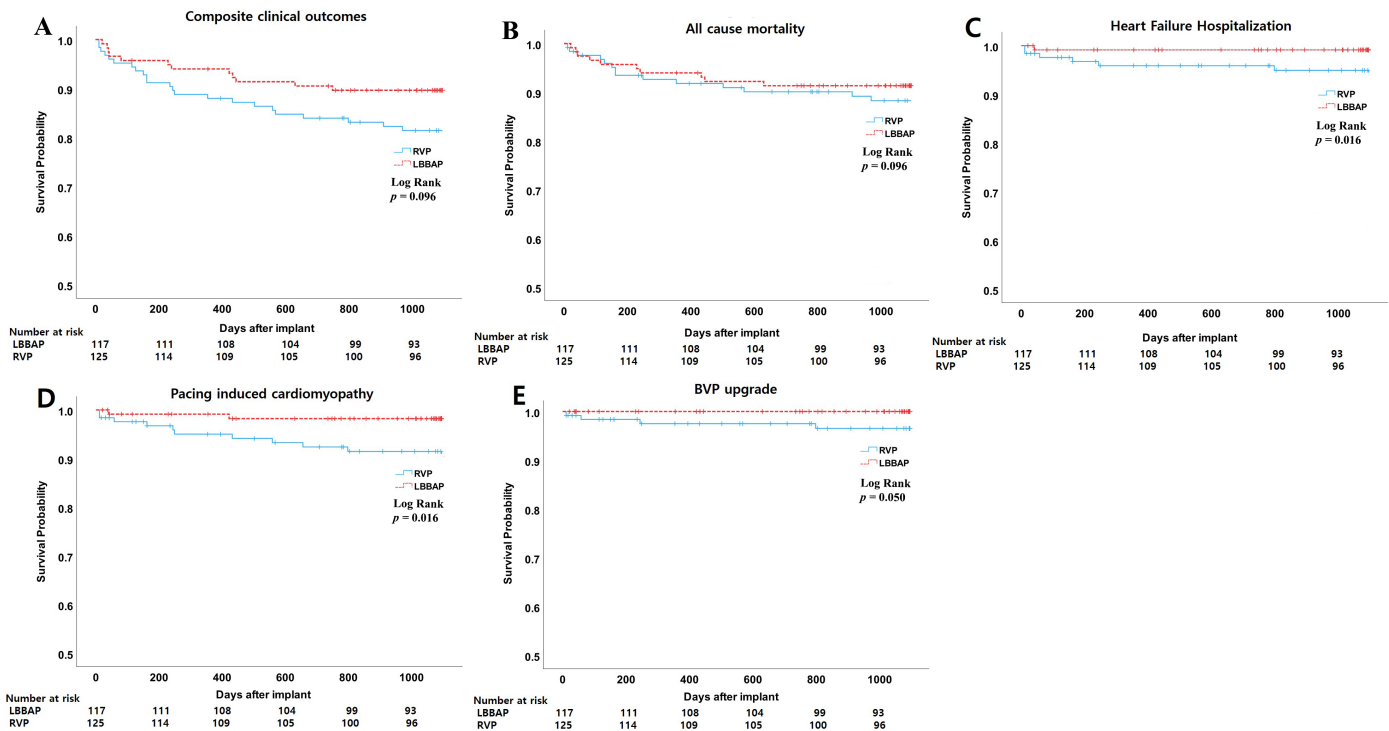


Figure 2

Kaplan-Meier survival curves for clinical outcomes. Time-to-event curves according to the pacing modality (LBBAP vs. RVP) over a 3-year clinical follow-up period. (A) Composite clinical outcomes. (B) All-cause mortality. (C) Heart failure hospitalization. (D) Pacing-induced cardiomyopathy (PICM). (E) Biventricular pacing (BVP) upgrade. Log-rank p-values and numbers at risk are presented in each panel. LBBAP, left bundle branch area pacing; RVP, right ventricular pacing

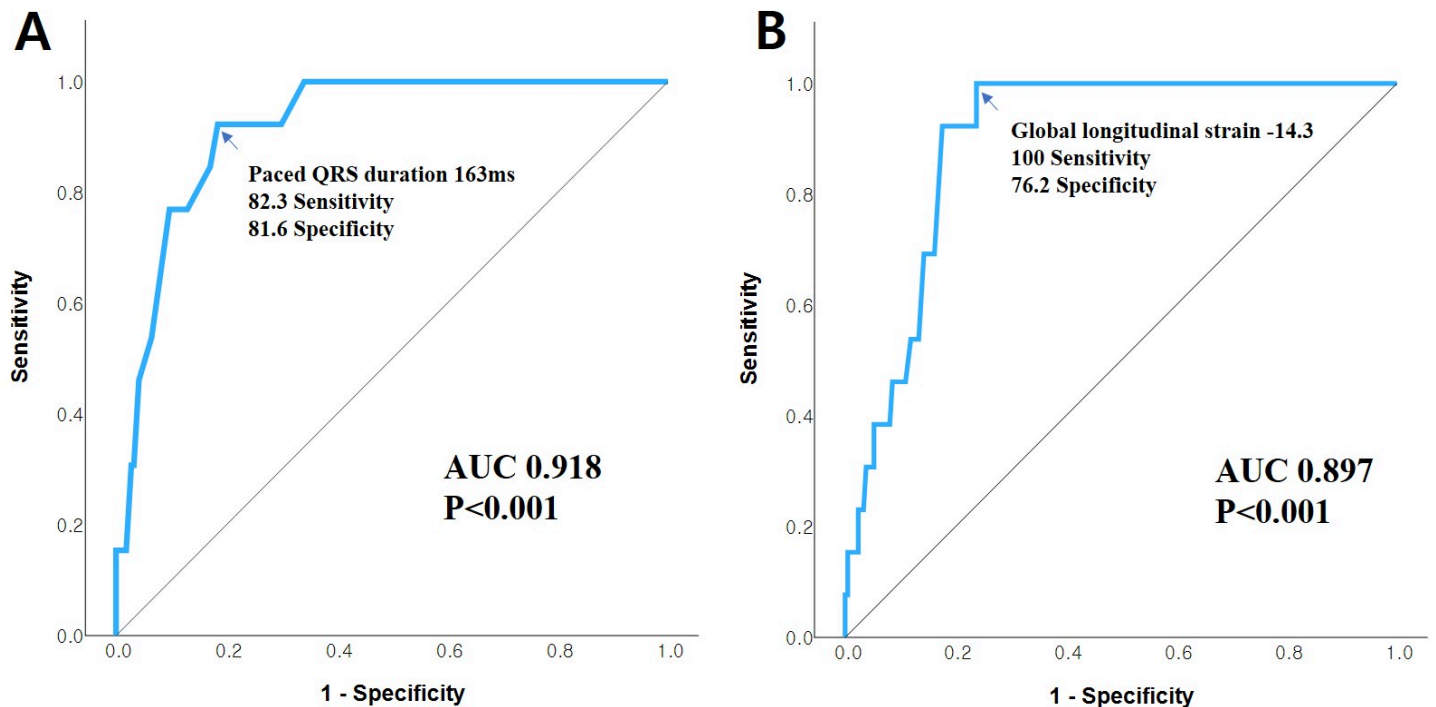


Figure 3

Receiver operating characteristic curve analysis for predicting pacing induced cardiomyopathy. (A)

Post-procedural paced QRS duration (pQRSd) cutoff of 163 ms yielded a sensitivity of 82.3% and a specificity of 81.6% (AUC: 0.918, 95% CI: 0.865–0.971, $p < 0.001$). **(B)** Early post-implant global longitudinal strain (GLS) cutoff of -14.3% yielded a sensitivity of 100% and a specificity of 76.2% (AUC: 0.897, 95% CI: 0.847–0.948, $p < 0.001$).