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Article

Effects of Left Bundle Branch Pacing and Right Ventricular Pacing on Blood Pressure and Cardiac Function in Patients With Bradyarrhythmia Complicated With Hypertension

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Abstract

Aims/Background: Individuals affected with bradyarrhythmia and hypertension exhibit distinct clinical manifestations. Arrhythmia is commonly managed with an artificial cardiac pacemaker. This study aims to investigate the effects of left bundle branch pacing (LBBP) and right ventricular septal pacing (RVSP) on blood pressure and cardiac function in patients with bradyarrhythmia and hypertension. **Methods**: This retrospective study included 1060 patients with bradyarrhythmia and hypertension who were treated in Xinhua Hospital Affiliated to Shanghai Jiaotong University School of Medicine between January 2020 and December 2023. According to the placement of cardiac pacing leads, patients were divided into the LBBP group (N = 260) and the RVSP group (N = 800). Baseline clinical characteristics were recorded, and intergroup comparisons were performed for postoperative blood pressure, cardiac function indicators, pacing parameters, QRS duration, and incidence of postoperative adverse events. **Results**: Postoperatively, the LBBP group demonstrated significantly lower systolic blood pressure (SBP) and pulse pressure (PP) compared to the RVSP group (both $p < 0.05$). Regarding the time $\times$ group interaction, the interaction was significant for PP and SBP ($p < 0.05$). Significant time effects were observed for left ventricular ejection fraction (LVEF), cardiac output (CO), and cardiac index (CI) in both groups (all $p < 0.05$), and the group effect was significant for CI ($p < 0.05$). Regarding ventricular pacing percentage, both groups showed a significant decrease over time ($p < 0.05$); the LBBP group exhibited a slightly lower percentage than the RVSP group ($p < 0.05$), with a significant time $\times$ group interaction ($p < 0.05$). Similarly, threshold decreased over time ($p < 0.05$), while perception and impedance remained stable ($p > 0.05$). The paced QRS duration was significantly narrower with LBBP during the follow-up period ($p < 0.05$). Additionally, no significant differences were observed in the incidence of adverse events between the two groups, indicating comparable safety profiles ($p > 0.05$). **Conclusion**: In patients with bradyarrhythmia and hypertension, LBBP offers significant therapeutic benefits in reducing SBP, pulse pressure, and QRS duration, while maintaining safety profiles and stable pacing parameters.

Keywords: bradyarrhythmia; hypertension; left bundle branch pacing; right ventricular septal pacing; blood pressure; cardiac function

1. Introduction

Bradyarrhythmia (BA) is a group of rhythm conditions manifested as reduced heart rate due to disrupted impulse generation or conduction. It usually includes conduction blocks and sick sinus diseases, and is often accompanied by symptoms like chest tightness, palpitations, syncope, and amaurosis. These malfunctions result from dysregulation in the cardiac conduction system or pacemaker function [1]. Sick sinus rhythm predominantly affects older adults, particularly those over 70 years of age, with an estimated incidence of about 1% [2]. The prevalence of atrioventricular block increases significantly with advancing age. Among them, the second-degree block appears more commonly in men, whereas the third-degree block is more frequently observed in patients with comorbid conditions such as diabetes and hypertension [3].

Hypertension is the most common cardiovascular disease globally and is a leading cause of morbidity and mortality [4,5]. The coexistence of bradyarrhythmia and hypertension is commonly reported and significantly increases the risk of adverse events such as syncope, heart failure and sudden cardiac death [6]. At present, bradyarrhythmia is primarily diagnosed using electrocardiogram (ECG) and long-term ECG monitoring [7], while the diagnosis and management of hypertension is generally well established [8,9]. However, pharmacological options for bradyarrhythmia are limited and are often associated with significant adverse reactions. Hence, permanent pacemaker implantation remains the primary treatment option, although the optimal site for ventricular electrode implantation continues to be controversial [10].

Traditionally, ventricular leads have been implanted in the right ventricle, commonly at the apex or the septum. Right ventricular septal pacing (RVSP) offers advantages, such as straightforward electrode fixation and a low risk of electrode dislocation. Despite these practical advantages, RVSP does not mimic the normal ventricular activation pattern of the heart, which can lead to delayed ventricular activation, bundle branch block, and, over time, an increased

risk of atrial fibrillation and heart failure [11]. The RVSP site is higher, which can improve the asynchrony of ventricular depolarization sequence and avoid the adverse effects of long-term apical pacing on cardiac hemodynamics and cardiac systolic and diastolic function. However, the optimal placement site is difficult to determine, and its physiological nature is also controversial [12].

Left bundle branch pacing (LBBP), first introduced in 2017, has emerged as a promising alternative. This approach aims to maintain the physiological sequence of ventricular activation by directly managing the conduction system. In theory, this method has the potential to improve electrical synchrony, help preserve cardiac function, and is associated with stable pacing parameters and a relatively simple implantation process [13]. Although early clinical evidence demonstrates potential advantages regarding cardiac function, its direct effect on systemic hemodynamics, especially blood pressure control in patients with coexisting bradyarrhythmia and hypertension, has not been fully elucidated [14].

Given this, the present study aims to compare left bundle branch region pacing with right ventricular septal pacing in individuals with bradyarrhythmia and hypertension. The ultimate goal is to examine their respective effects on blood pressure control and cardiac performance, thereby providing a basis for the most appropriate pacing approach selection for this high-risk population.

2. Methods

2.1 Selection of Study Participants

This retrospective study enrolled 1060 bradyarrhythmia patients comorbid with hypertension who received permanent dual-chamber pacemaker implantation at the Department of Cardiology, Xinhua Hospital Affiliated to Shanghai Jiaotong University School of Medicine, between January 2020 and December 2023 (Fig. 1). Based on the implantation site of the cardiac pacing electrode, patients were divided into the left bundle branch pacing (LBBP) group (N = 260) and the right ventricular septal pacing (RVSP) group (N = 800).

2.2 Inclusion and Exclusion Criteria

Patients were included if they met the following criteria: (1) fulfilled the indications for permanent cardiac pacemaker implantation [1] and met the diagnostic criteria of both hypertension [15] and bradyarrhythmia [16]; (2) received first-time cardiac pacemaker implantation; (3) had a left ventricular ejection fraction (LVEF) >40%; (4) completed regular follow-up for 12 months after the surgery; and (5) had complete clinical records.

However, patients were excluded if they had (1) definite secondary hypertension, including primary aldosteronism, pheochromocytoma, renovascular hypertension, and hyperthyroidism; (2) coagulation abnormalities; (3) advanced cardiac failure, such as grade III–IV, with poor surgical tolerance; (4) significant liver and kidney dysfunction; (5) congenital heart disease or persistent atrial fibrillation; (6) conditions limiting the supine position, such as trauma or spinal deformities; (7) a need for continuous use of antiplatelet or anticoagulant drugs during the perioperative period; and (8) those with acute or chronic infections.

2.3 Cardiac Pacemaker Implantation Protocol

In the LBBP group, pacemaker leads were placed in the left bundle branch area. Under a right anterior oblique 30° X-ray fluoroscopy, a C315-HIS delivery sheath (Medtronic, Minneapolis, MN, USA) was advanced into the right ventricle along with a guide wire. A 3830 electrode was placed and advanced carefully toward the target site. Once the lead crossed the tricuspid valve, the electrode tip and sheath tube were guided to the lower third of the interventricular septum, targeting the region approximately 1–2 cm inferior to the recording site of the His bundle, which is typically visualized on fluoroscopy as the area where the septum is thickest. The 3830 electrode was initially rotated clockwise (3–4 turns) to achieve fixation within the interventricular septum. In the left anterior oblique position, the sheath was rotated counterclockwise to align perpendicular to the interventricular septum, followed by further clockwise rotations (6–8 turns) to secure deep septal engagement. To confirm appropriate lead placement, monopolar pacing (2 V at 0.4 ms) was performed, and the morphology of the QRS wave in lead V1 was assessed. The terminal r/R wave with a narrow QRS complex indicated that the pacing electrode was placed in the left bundle branch area. If this pattern was not found, the electrode was gradually advanced and repositioned. Once desirable pacing parameters and lead stability were confirmed, the guide wire was withdrawn, and the procedure was completed.

Patients in the RVSP group were implanted with a pacemaker in the right ventricular septum using a similar subclavian vein access. Under the right anterior oblique 30° X-ray fluoroscopy, an active spiral electrode was placed in the mid-to-lower septal region of the right ventricle. Left anterior oblique 45° imaging was then used to confirm its orientation, ensuring that the electrode tip was pointed toward the spine without crossing it and remained perpendicular to the ventricular septum. Under the posterior-anterior fluoroscopy, the electrode position was further verified within the appropriate anatomical region (between 1.5 and 2.0 cones from the bottom of the heart shadow, the right atrioventricular valve, and the apex).

The electrocardiogram revealed a widened QRS wave duration, leftward axis deviation, an R-type in lead I, and a left bundle branch block pattern in the precordial leads, all consistent with right ventricular septal pacing. After confirming effective pacing and stable electrical parameters, the guiding wire was withdrawn, and the implantation procedure was completed.

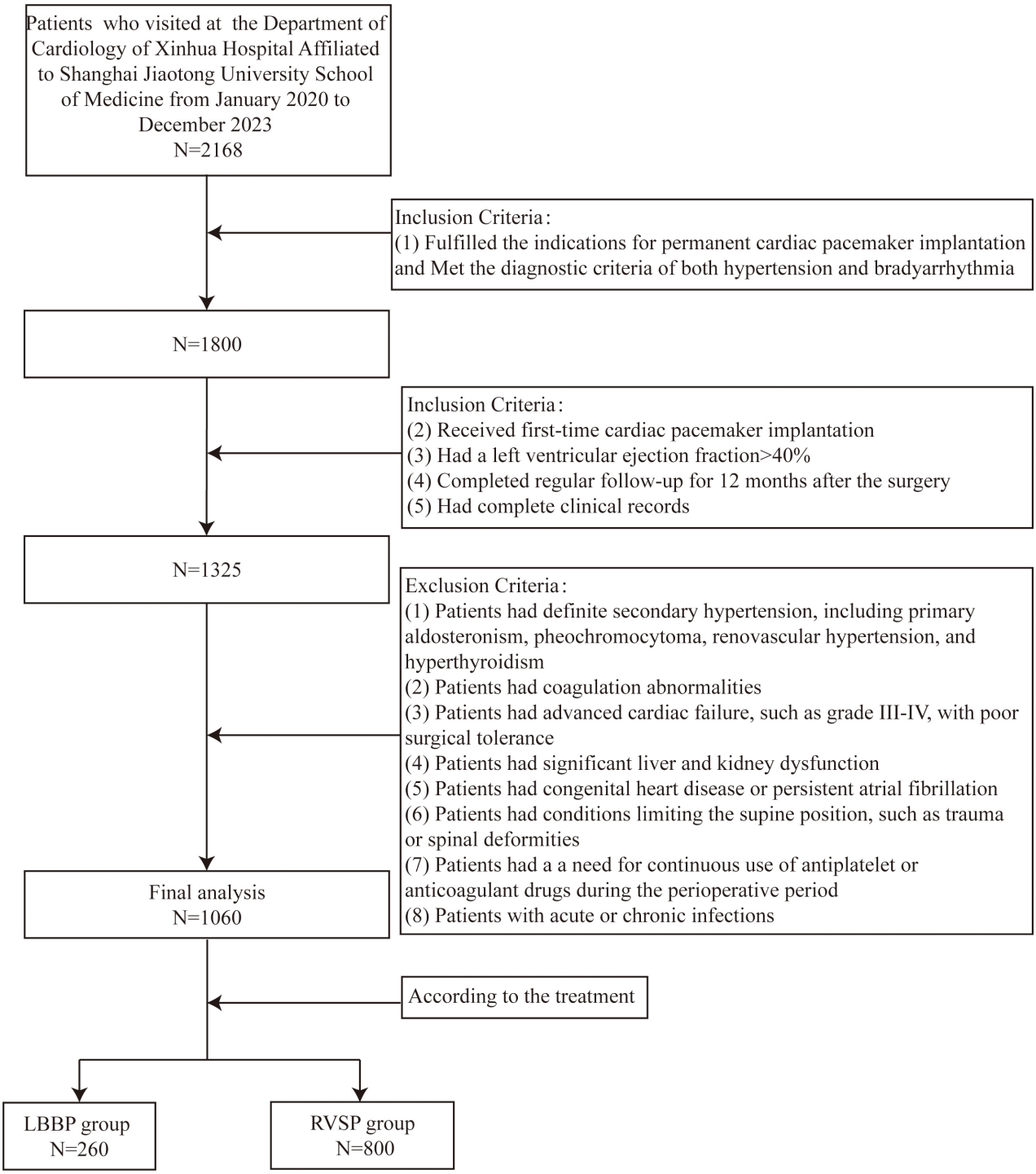

Fig. 1. Flowchart of Study Participant Selection. LBBP, left bundle branch pacing; RVSP, right ventricular septal pacing.

2.4 Observed Indices

(1) Clinical Characteristics: Baseline clinical data included age, sex, body mass index (BMI), type of bradyarrhythmia, systolic blood pressure (SBP), diastolic blood pressure (DBP), pulse pressure, New York Heart Association (NYHA) cardiac function classification, heart rate, left ventricular ejection fraction (LVEF), cardiac output (CO), and cardiac index (CI), QRS duration (QRSd) and operation time. Operation time was defined as the interval from skin incision to final wound closure, including all procedural steps such as lead placement, pocket creation, pacing parameter testing, and wound suturing.

(2) Blood pressure evaluation: Blood pressure data were retrospectively extracted from the electronic medical record system. Baseline blood pressure values were calculated as the average of at least two readings taken at rest after hospital admission and before pacemaker implantation, using a calibrated electronic sphygmomanome-

Table 1. Comparison of baseline clinical and demographic characteristics between groups.

Indicator	RVSP (N = 800)	LBBP (N = 260)	$t/Z/\chi^2$	p-value
Age [years, M (Q1, Q3)]	67 (63, 72)	68 (61, 77)	1.552	0.121
Sex			0.947	0.330
Male (n, %)	440 (55.00)	134 (51.54)		
Female (n, %)	360 (45.00)	126 (48.46)		
BMI [kg/m^2, M (Q1, Q3)]	24.02 (23.13, 24.93)	23.77 (22.80, 25.00)	1.753	0.080
Type of bradyarrhythmia			0.714	0.700
SSS (n, %)	270 (33.75)	87 (33.46)		
AVB (n, %)	432 (54.00)	136 (52.31)		
SSS and AVB (n, %)	98 (12.25)	37 (14.23)		
NYHA cardiac functional grading			0.177	0.674
I (n, %)	338 (42.25)	106 (40.77)		
II (n, %)	462 (57.75)	154 (59.23)		
Heart rate [beats per minute, M (Q1, Q3)]	48 (45, 51)	47 (45, 50)	1.563	0.118
Time of operation (min, mean $\pm$ SD)	98.84 $\pm$ 20.17	97.49 $\pm$ 19.58	0.943	0.346
SBP (mmHg, mean $\pm$ SD)	150.78 $\pm$ 6.56	150.83 $\pm$ 6.75	0.107	0.915
DBP (mmHg, mean $\pm$ SD)	68.27 $\pm$ 7.69	67.82 $\pm$ 5.62	0.879	0.379
PP (mmHg, mean $\pm$ SD)	82.50 $\pm$ 10.15	83.01 $\pm$ 8.25	0.728	0.467
LVEF (%, mean $\pm$ SD)	47.54 $\pm$ 3.25	47.68 $\pm$ 3.83	0.599	0.549
CO (L/min, mean $\pm$ SD)	4.55 $\pm$ 0.56	4.52 $\pm$ 0.64	0.739	0.460
CI (L/min·m^2, mean $\pm$ SD)	2.76 $\pm$ 0.30	2.72 $\pm$ 0.32	1.602	0.109
QRSd (ms, mean $\pm$ SD)	120.38 $\pm$ 10.53	120.71 $\pm$ 9.44	0.472	0.637

BMI, body mass index; SSS, sick sinus syndrome; AVB, atrioventricular block; NYHA, New York Heart Association; SBP, systolic blood pressure; DBP, diastolic blood pressure; LVEF, left ventricular ejection fraction; QRSd, QRS duration; CO, cardiac output; CI, cardiac index; PP, pulse pressure; SD, standard deviation; M, median.

ter [HBP-1300, Omron (Dalian) Co., Ltd., Dalian, China]. During follow-up, blood pressure was recorded at 1, 6, and 12 months during outpatient visits after the procedure. All measurements were performed following a standardized protocol: patients rested in a seated position for at least 5 minutes, and at least two readings were obtained using the same type of calibrated electronic sphygmomanometer (unified model), and the average value was recorded. This protocol was consistent with baseline measurements to minimize variability. The primary indices analyzed were systolic blood pressure (SBP), diastolic blood pressure (DBP), and pulse pressure (PP). To further evaluate the intervention effect of pacing modality, changes in blood pressure (Δ values, the follow-up value minus the baseline value) were calculated for each follow-up time point relative to baseline.

(3) Cardiac function assessment: Echocardiography (Philips iE Elite color Doppler ultrasound diagnostic instrument) was performed before pacemaker implantation (baseline) and repeated at 1 month, 6 months and 12 months postoperatively. A three-dimensional X5-1 matrix probe (frequency range 1.0 MHz–5.0 MHz) was used in this procedure. Routine cardiac function indicators were recorded, including left ventricular ejection fraction (LVEF), cardiac output (CO), and cardiac index (CI). Preoperative baseline values of these cardiac function parameters were used for longitudinal comparison.

(4) Pacemaker programmable parameters: The pacing parameters were assessed using a Medtronic 2090 pacemaker instrument by the same experienced physician to ensure consistency. These parameters included pacing perception (ventricular perception normal value $\geq$5 mV), pacing threshold (normal value $\leq$1.0 V), pacing impedance (normal value 300~1000 Ω) and the percentage of ventricular pacing (VP%). Measurements were recorded immediately after implantation and repeated at 1, 6, and 12 months postoperatively. The intraoperative VP% was calculated as the average proportion of ventricular pacing during the entire lead testing and parameter optimization procedure, including intermittent pauses for sensing assessment and intrinsic rhythm observation.

(5) Electrocardiographic assessment: Standard 12-lead electrocardiography (SE-18, Edan Instruments, Inc., Shenzhen, China) was performed before pacemaker implantation (baseline) and during follow-up visits at 1, 6, and 12 months. QRS duration (QRSd) was measured by the same senior physician electrocardiographer. QRSd was defined as the time interval from the onset to the end of the QRS complex, and the average value of three consecutive cardiac cycles was used for analysis.

(6) Adverse events: Adverse events occurring within 12 months after surgery were documented, including pacemaker implantation-related complications and major cardiovascular events.

Table 2. Comparison of postoperative blood pressure between the two groups of patients.

Indicator	Time	RVSP (N = 800)	LBBP (N = 260)
SBP (mmHg, mean ± SD)	Before the operation	150.78 ± 6.56	150.83 ± 6.75
	1 month after the operation	146.59 ± 7.02	144.71 ± 6.29
	6 months after the operation	146.60 ± 7.16	144.82 ± 5.18
	12 months after the operation	146.60 ± 6.72	144.33 ± 6.61
Results of repeated measures analysis of variance Time effect: F = 115.861, $p < 0.001$ Group effect: F = 36.985, $p < 0.001$ Time × group interaction effect: F = 4.749, $p = 0.003$			
Indicator	Time	RVSP (N = 800)	LBBP (N = 260)
DBP (mmHg, mean ± SD)	Before the operation	68.27 ± 7.69	67.82 ± 5.62
	1 month after the operation	70.36 ± 8.28	70.61 ± 5.66
	6 months after the operation	70.50 ± 9.60	70.64 ± 5.66
	12 months after the operation	71.10 ± 9.47	70.61 ± 5.64
Results of repeated measures analysis of variance Time effect: F = 20.158, $p < 0.001$ Group effect: F = 0.023, $p = 0.879$ Time × group interaction effect: F = 1.174, $p = 0.317$			
Indicator	Time	RVSP (N = 800)	LBBP (N = 260)
PP (mmHg, mean ± SD)	Before the operation	82.50 ± 10.15	83.01 ± 8.25
	1 month after the operation	76.23 ± 9.90	74.33 ± 7.42
	6 months after the operation	76.10 ± 10.89	73.52 ± 7.80
	12 months after the operation	75.50 ± 10.84	74.29 ± 7.60
Results of repeated measures analysis of variance Time effect: F = 129.162, $p < 0.001$ Group effect: F = 11.616, $p < 0.001$ Time × group interaction effect: F = 3.757, $p = 0.011$			

2.5 Statistical Analysis

Statistical analyses were conducted using SPSS version 27.0 (IBM, Armonk, NY, USA). Data distribution was examined using the Kolmogorov–Smirnov test. The measurement data conforming to the normal distribution were expressed as mean ± standard deviation (mean ± SD) and compared using the independent sample *t*-test. Non-normally distributed variables were expressed as median with interquartile range, and the Mann–Whitney U rank sum test was used for group comparisons. For measurements collected at multiple time points, repeated measures analysis of variance and generalized estimating equations were used to determine changes over time. Categorical variables were expressed as counts and percentages, and analyzed using the chi-square (χ^2) test, chi-square correction, or Fisher's exact, as appropriate. A *p*-value of <0.05 was considered statistically significant.

3. Results

3.1 Comparison of Clinical Characteristics Between the Two Groups of Patients

Out of the total 1060 patients, 800 received RVSP and 260 underwent LBBP. The overall mean LVEF was 47.57 ± 3.40%. The distribution of bradyarrhythmia types revealed that 33.68% of patients had sick sinus syndrome and 53.58% had atrioventricular block, while 12.74% of patients met more than one pacing indication. As shown in Table 1, no significant intergroup difference was observed in baseline characteristics, including age, sex, BMI, type of bradyarrhythmia, cardiac function classification, heart rate, operation time, and baseline measures of SBP, DBP, PP, LVEF, CO, CI and QRSd ($p > 0.05$).

3.2 Intergroup Comparison of Postoperative Blood Pressure

Table 2 reveals that repeated-measures analysis of variance (ANOVA) detected significant time-related changes in SBP, DBP and PP in both the RVSP and LBBP groups (all $p < 0.05$). During the follow-up period, SBP and PP gradually decreased, while DBP demonstrated a slight increase. The overall intergroup comparison showed significantly lower SBP and PP levels in the LBBP group compared with the RVSP group ($p < 0.05$), whereas DBP did not differ between groups ($p > 0.05$). A significant time × group interaction effect was observed for SBP and PP ($p < 0.05$), suggesting that the decrease in the LBBP group was more pronounced. In contrast, no significant interaction effect was observed for DBP ($p > 0.05$), indicating that both groups followed a similar trend of changes over time.

Table 3. Comparison of blood pressure changes between the two groups after surgery.

Indicator	Time	RVSP (N = 800)	LBBP (N = 260)
ΔSBP [mmHg, M (Q1, Q3)]	1 month after the operation	–4 (–11, 3)	–6 (–13, 0.25)
	6 months after the operation	–4 (–11, 3)	–6 (–11, 0)
	12 months after the operation	–4 (–10, 2)	–7 (–13, 0)
Generalized Estimating Equations			
Time effect: Wald $\chi^2 = 0.612$, $p = 0.736$			
Group effect: Wald $\chi^2 = 13.854$, $p < 0.001$			
Time × group interaction effect: Wald $\chi^2 = 0.647$, $p = 0.724$			
Indicator	Time	RVSP (N = 800)	LBBP (N = 260)
ΔDBP [mmHg, M (Q1, Q3)]	1 month after the operation	2 (–6, 10)	2 (–3, 8)
	6 months after the operation	1 (–8, 8.25)	4 (–2, 9)
	12 months after the operation	1 (–9, 9)	3 (–3, 8)
Generalized Estimating Equations			
Time effect: Wald $\chi^2 = 41.163$, $p < 0.001$			
Group effect: Wald $\chi^2 = 0.086$, $p = 0.769$			
Time × group interaction effect: Wald $\chi^2 = 5.540$, $p = 0.063$			
Indicator	Time	RVSP (N = 800)	LBBP (N = 260)
ΔPP [mmHg, M (Q1, Q3)]	1 month after the operation	–6 (–16, 3)	–8 (–14, –3)
	6 months after the operation	–7 (–17, 5)	–10 (–15, 3)
	12 months after the operation	–7 (–17, 4)	–9 (–14, 3)
Generalized Estimating Equations			
Time effect: Wald $\chi^2 = 2.768$, $p = 0.251$			
Group effect: Wald $\chi^2 = 14.445$, $p < 0.001$			
Time × group interaction effect: Wald $\chi^2 = 3.532$, $p = 0.171$			

As detailed in Table 3, generalized estimating equation analysis further revealed that group effects in terms of ΔSBP were statistically significant ($p < 0.05$), indicating a clear difference in the degree of SBP reduction between the two approaches. However, the time and the time × group interaction effect was not statistically significant ($p > 0.05$), suggesting that the magnitude of SBP reduction in the LBBP group relative to the RVSP group remained consistent over the follow-up period without further divergence.

Regarding ΔDBP, only the effect of time was statistically significant ($p < 0.05$), while the between-group effect and interaction effect did not reach statistical significance. This indicates that the time-dependent trends of DBP in both groups followed a similar trajectory, with no significant differences observed between groups. For changes in PP (ΔPP), only group effect was statistically significant ($p < 0.05$), indicating that the LBBP group experienced a greater reduction in postoperative PP compared to the RVSP group.

3.3 Intergroup Comparison of Postoperative Cardiac Function

Comparison of cardiac function parameters is presented in Table 4. Repeated-measures ANOVA identified significant time-dependent changes in LVEF, CO, and CI in both groups (all $p < 0.05$). LVEF increased between 1 and 6 months after surgery, followed by a slight decline at 12 months. In contrast, CO and CI did not change significantly, but increased after implantation and remained stable during follow-up. The overall intergroup comparison revealed no significant differences in LVEF and CO between the LBBP and RVSP groups ($p > 0.05$), indicating that the two groups did not differ in these parameters across the entire follow-up period. However, a significant group effect was observed for CI ($p < 0.05$), with the CI level in the LBBP group being consistently lower than that in the RVSP group after surgery. Additionally, the time × group interaction effect for LVEF, CO, and CI was not statistically significant (all $p > 0.05$), indicating that the trajectories of these cardiac function parameters over time were similar between the two groups.

3.4 Comparison of Pacing Parameters Between the Two Groups

As shown in Table 5, repeated measures ANOVA identified a significant effect of time on pacing threshold and the proportion of ventricular pacing ($p < 0.05$), with both parameters declining during follow-up. In contrast, perception and lead impedance showed no significant changes over time and remained relatively stable throughout the follow-up period (all $p > 0.05$). The overall between-group comparison revealed a significant difference in the percentage of ventricular pacing ($p < 0.05$),

Table 4. Comparison of postoperative cardiac function between the two groups.

Indicator	Time	RVSP (N = 800)	LBBP (N = 260)
LVEF (%, mean ± SD)	Before the operation	47.54 ± 3.25	47.68 ± 3.83
	1 month after the operation	50.93 ± 4.18	51.08 ± 5.29
	6 months after the operation	51.54 ± 5.06	51.67 ± 6.32
	12 months after the operation	51.23 ± 6.89	50.76 ± 6.81
Results of repeated measures analysis of variance			
Time effect: F = 96.101, $p < 0.001$			
Group effect: F = 0.003, $p = 0.954$			
Time × group interaction effect: F = 0.682, $p = 0.541$			
Indicator	Time	RVSP (N = 800)	LBBP (N = 260)
CO (L/min, mean ± SD)	Before the operation	4.55 ± 0.56	4.52 ± 0.64
	1 month after the operation	4.64 ± 0.49	4.61 ± 0.47
	6 months after the operation	4.62 ± 0.50	4.60 ± 0.65
	12 months after the operation	4.64 ± 0.54	4.65 ± 0.57
Results of repeated measures analysis of variance			
Time effect: F = 9.334, $p < 0.001$			
Group effect: F = 0.379, $p = 0.538$			
Time × group interaction effect: F = 0.366, $p = 0.770$			
Indicator	Time	RVSP (N = 800)	LBBP (N = 260)
CI (L/min·m^2, mean ± SD)	Before the operation	2.76 ± 0.30	2.72 ± 0.32
	1 month after the operation	2.81 ± 0.24	2.78 ± 0.22
	6 months after the operation	2.80 ± 0.25	2.78 ± 0.34
	12 months after the operation	2.81 ± 0.27	2.81 ± 0.27
Results of repeated measures analysis of variance			
Time effect: F = 9.374, $p < 0.001$			
Group effect: F = 5.846, $p = 0.016$			
Time × group interaction effect: F = 0.398, $p = 0.748$			

along with a significant interaction effect of time × group ($p < 0.05$), indicating that the proportion of ventricular pacing varied between the two groups over time. In addition, analysis of between-group effects and time × group interaction effects showed no significant differences in threshold, perception, or impedance (all $p > 0.05$), indicating that both pacing approaches showed comparable stability throughout the follow-up period.

3.5 Comparison of Postoperative QRSd Between the Two Groups of Patients

Repeated-measures ANOVA identified a significant time effect and a significant group effect in QRSd of the two groups of patients ($p < 0.05$). The overall intergroup comparisons demonstrated significantly narrower QRSd in the LBBP group compared with the RVSP group. Furthermore, a significant time × group interaction was also observed ($p < 0.05$), suggesting that the temporal trajectories of QRSd differed between the two pacing modalities, with the LBBP group maintaining more stable and narrower QRS complexes over time compared with the RVSP group (Table 6).

3.6 Incidence of Adverse Events Across the Two Groups of Patients

The incidence of adverse events in both the study groups over the follow-up period is presented in Table 7. Overall, there were no significant differences in the incidence of cardiovascular events and pacemaker implantation-related complications between the two groups ($p > 0.05$). The overall rate of adverse events was 4.75% in the RVSP group and 7.69% in the LBBP group; however, this difference did not reach statistical significance ($p > 0.05$). These results indicate that both pacing strategies have a comparable safety profile during the observed period.

4. Discussion

This study evaluated the effects of LBBP and RVSP on blood pressure, cardiac function indicators, pacing parameters, QRSd and the incidence of postoperative adverse events in patients with bradyarrhythmia and hypertension. The results confirmed that compared with RVSP, LBBP can effectively reduce SBP and pulse pressure, maintain hemodynamic stability, and preserve left ventricular electrical

Table 5. Comparison of pacing parameters between the two groups.

Indicator	Time	RVSP (N = 800)	LBBP (N = 260)
Threshold (V, mean ± SD)	Immediately during the operation	0.84 ± 0.15	0.83 ± 0.15
	1 month after the operation	0.76 ± 0.21	0.76 ± 0.16
	6 months after the operation	0.77 ± 0.18	0.75 ± 0.22
	12 months after the operation	0.76 ± 0.22	0.74 ± 0.20
Results of repeated measures analysis of variance Time effect: F = 37.303, $p < 0.001$ Group effect: F = 3.485, $p = 0.062$ Time × group interaction effect: F = 0.531, $p = 0.652$			
Indicator	Time	RVSP (N = 800)	LBBP (N = 260)
Perception (mV, mean ± SD)	Immediately during the operation	9.97 ± 1.18	9.95 ± 1.31
	1 month after the operation	9.99 ± 1.37	9.93 ± 1.57
	6 months after the operation	10.07 ± 1.05	10.08 ± 1.34
	12 months after the operation	9.98 ± 1.17	9.97 ± 1.46
Results of repeated measures analysis of variance Time effect: F = 1.567, $p = 0.196$ Group effect: F = 0.125, $p = 0.724$ Time × group interaction effect: F = 0.089, $p = 0.964$			
Indicator	Time	RVSP (N = 800)	LBBP (N = 260)
Impedance (Ω, mean ± SD)	Immediately during the operation	726.94 ± 97.37	719.53 ± 100.32
	1 month after the operation	723.48 ± 75.53	720.93 ± 72.03
	6 months after the operation	725.48 ± 75.20	725.93 ± 79.37
	12 months after the operation	722.96 ± 73.63	718.19 ± 68.76
Results of repeated measures analysis of variance Time effect: F = 0.562, $p = 0.630$ Group effect: F = 1.451, $p = 0.229$ Time × group interaction effect: F = 0.338, $p = 0.786$			
Indicator	Time	RVSP (N = 800)	LBBP (N = 260)
Ventricular pacing (%)	Immediately during the operation	95.29 ± 3.00	94.89 ± 2.70
	1 month after the operation	77.18 ± 6.44	77.66 ± 11.46
	6 months after the operation	63.61 ± 11.96	61.34 ± 14.72
	12 months after the operation	62.29 ± 11.35	60.64 ± 11.56
Results of repeated measures analysis of variance Time effect: F = 1948.206, $p < 0.001$ Group effect: F = 7.403, $p = 0.007$ Time × group interaction effect: F = 3.405, $p = 0.027$			

synchronization. Overall, LBBP showed better clinical outcomes in such patients who have indications for pacing therapy.

The present study demonstrates that both pacing approaches significantly reduced SBP and pulse pressure after implantation of the two pacemakers. The possible reason is that after the pacing treatment, the heart rate of the patients was higher than before, and the physiological effect caused by bradycardia was reversed, leading to the ventricular diastolic blood volume returning to a normal level and resulting in a decrease in SBP [17]. However, further dynamic analysis of changes in blood pressure (ΔSBP, ΔDBP, ΔPP) revealed that LBBP and RVSP differed significantly in regulating postoperative SBP and PP, with the LBBP group showing greater reductions compared with the RVSP group. The lack of a significant time × group interaction for ΔSBP ($p = 0.724$) indicates that this advantage appeared early after implantation and remained stable throughout the 12-month follow-up, rather than progressively increasing over time. The observed effect of LBBP on blood pressure may be due to its ability to restore a physiological ventricular activation pattern. Unlike the asynchronous electrical activity induced by RVSP, LBBP directly captures the left bundle branch, so that the electrical pulse is rapidly transmitted along the high-speed His-Purkinje system to achieve left ventricular synchronous electromechanical contraction. This enhanced electromechanical synchrony recovery may optimize ventricular-arterial coupling, reduce systolic load, and improve the arterial elasticity function, thereby reducing systolic blood pressure while maintaining diastolic blood pressure and significantly narrowing pulse pressure [18,19].

Table 6. Comparison of postoperative QRSd between the two groups of patients.

	Time	RVSP (N = 800)	LBBP (N = 260)
Native QRSd (ms, mean ± SD)	Before the operation	120.38 ± 10.53	120.71 ± 9.44
Paced QRSd (ms, mean ± SD)	1 month after the operation	135.41 ± 16.15	127.89 ± 9.37
	6 months after the operation	136.15 ± 16.79	128.68 ± 9.71
	12 months after the operation	134.43 ± 10.45	128.67 ± 9.38
Results of repeated measures analysis of variance			
Time effect: F = 152.356, $p < 0.001$			
Group effect: F = 122.310, $p < 0.001$			
Time × group interaction effect: F = 16.407, $p < 0.001$			

Table 7. The incidence of adverse events across the two groups of patients.

Adverse event	RVSP (N = 800)	LBBP (N = 260)	χ^2	p-value
Cardiovascular events				
Rehospitalization due to heart failure	13 (1.63)	6 (2.31)	0.204	0.651
Atrial fibrillation	12 (1.50)	8 (3.08)	1.853	0.173
Pacemaker implantation-related complications				
Pocket hematoma	5 (0.63)	3 (1.15)	0.197	0.657
Lead dislodgment/displacement	4 (0.50)	0 (0.00)	/	0.577
Pericardial effusion	1 (0.13)	1 (0.38)	/	0.431
Significant threshold elevation	3 (0.38)	2 (0.77)	0.081	0.776
Total	38 (4.75)	20 (7.69)	3.284	0.070

"Total" in this table records the number of patients who experienced at least one event.

RVSP, a conventional pacing approach, has long been associated with unresolved issues, including electromechanical asynchrony, impaired contractile efficiency, and elevated risks of heart failure and death [20,21]. In contrast, LBBP enables direct left bundle branch capture via deep septal pacing, representing a novel and promising pacing strategy. This study assessed its capacity to maintain favorable electromechanical synchronization. QRSd has been considered as an alternative indicator of electrical synchrony [22], and narrow QRSd has been associated with good ventricular synchronization [23,24]. During LBBP, the left ventricular His-Purkinje system is quickly engaged, yielding superior electrical synchronization and narrower paced QRS complexes. In our study, compared with RVSP, LBBP resulted in persistently shorter QRSd at 1, 6, and 12 months post-implantation, aligning with findings from earlier investigations [25,26,27]. These findings support that LBBP preserves superior electrical synchrony, which may alleviate ventricular load and lower arrhythmia susceptibility. In the present study, no significant differences were observed between the two groups in the incidence of cardiovascular events or pacemaker implantation-related complications. This finding may be related to several factors, such as the relatively small sample size, potential selection bias, and the retrospective design of the study. Therefore, larger, multicenter randomized controlled studies are needed to further validate the safety outcomes of these approaches. Additionally, there was no significant difference in pacing parameters, including threshold, perception, and impedance, between the LBBP and RVSP groups at 1 month, 6 months and 12 months after operation, suggesting that LBBP offers stable pacing performance over time and further supports its safety and clinical feasibility.

Our findings showed that the ventricular pacing percentage significantly decreased over time in both groups, with LBBP exhibiting a slightly lower percentage than RVSP and a significant time-group interaction. Although LBBP may reduce unnecessary right ventricular pacing, the percentage remained >60% at 12 months, reflecting high pacing dependence of patients with atrioventricular block (AVB), and further long-term studies are warranted to elucidate the clinical implications of these findings. Of note, the intraoperative VP% of approximately 95% reflects the average pacing burden during the entire testing procedure, which included intermittent pauses for standard assessments. This does not indicate a lead malfunction. Instead, it reflects the fact that the intraoperative VP% was calculated as the average pacing burden throughout the lead testing and parameter optimization procedure. During implantation, pacing output is intermittently paused at intervals for essential assessments, including sensing threshold measurement, lead stability testing, and intrinsic rhythm observation. These intermittent pauses, which are part of standard implantation practice, result in a cumulative VP% that is expected to be slightly below 100%.

Although the left ventricular ejection fraction and cardiac output in the LBBP group were numerically comparable to those in the RVSP group, this may be due to the lim-

ited follow-up time and relatively small sample size. Notably, the CI value in the LBBP group was slightly lower than that observed in the RVSP group, which may reflect subtle effects of left ventricular septal pacing on local systolic and diastolic function, or it may be related to preoperative hemodynamic differences and variations in pacing parameter settings between patients. Therefore, the overall clinical advantages of LBBP still need further validation through extensive studies.

We acknowledge several limitations in this study. Firstly, a significant imbalance existed in sample sizes between the LBBP group (N = 260) and the RVSP group (N = 800). Given the rapid adoption of LBBP technology during the later years of the study period (2020 to 2023), the LBBP cohort likely comprised predominantly recent cases, whereas the RVSP cohort consisted mainly of earlier cases. This temporal variation may introduce potential selection bias, as patient selection, operator experience, and clinical management approaches might have evolved. Second, this was a single-center retrospective study. Although the baseline characteristics between groups were generally balanced, the impact of residual or unmeasured confounding factors cannot be completely excluded. Third, the follow-up period was relatively short (12 months), which may not fully capture the long-term hemodynamic effects and clinical outcomes of the two pacing approaches. Finally, more sensitive biomarkers reflecting cardiac stress load, such as pro-B-type natriuretic peptide (proBNP), were not included in this analysis. The absence of these indicators limits a more comprehensive assessment of the physiological benefits of LBBP. Future prospective studies should systematically include tools such as proBNP and ambulatory blood pressure monitoring to provide a more comprehensive evaluation of the long-term clinical impact of LBBP. This study excluded patients requiring use of anticoagulant or antiplatelet drugs during the perioperative period. In clinical practice, although such patients represent a relatively small proportion, they are a special population due to their increased bleeding risk. Therefore, the study conclusions have a certain selection bias and cannot be directly generalized to all target patients. Caution should be exercised when extrapolating the findings.

5. Conclusion

In summary, compared with RVSP, LBBP can effectively reduce postoperative SBP, pulse pressure, and QRSd in patients with bradyarrhythmia and hypertension. These observations support the potential role of LBBP as a promising pacing approach in this specific population.

Key Points

• Bradyarrhythmia and hypertension frequently coexist and are associated with elevated cardiovascular risks, including syncope, heart failure, and sudden cardiac death.

• Postoperatively, LBBP significantly reduced SBP and PP compared with RVSP, along with greater absolute reductions (ΔSBP, ΔPP) that followed a sustained downward trajectory.

• There was no significant difference in cardiac function parameters (LVEF, CO) between groups, while the cardiac index (CI) differed substantially.

• The postoperative QRS duration was significantly shorter in the LBBP group than that of the RVSP group, indicating improved left ventricular electrical synchrony.

• Both pacing approaches showed comparable safety profiles and stable pacing parameters during the follow-up period.

Availability of Data and Materials

The data analyzed are available upon request from the corresponding author.

Author Contributions

XML and BL had the original conception of the work. RZ and XMY collected the clinical data. YGL performed the research. XML and BL drafted the manuscript. All authors contributed to the important editorial changes in the manuscript. 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

This study was approved by the Ethics Committee of Xinhua Hospital Affiliated to Shanghai Jiaotong University School of Medicine (Approval No.: XHEC-D-2025-152) and strictly adheres to the Declaration of Helsinki. All patients have signed a written informed consent form.

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Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] Kusumoto FM, Schoenfeld MH, Barrett C, Edgerton JR, Ellenbogen KA, Gold MR, et al. 2018 ACC/AHA/HRS Guideline on the Evaluation and Management of Patients With Bradycardia and Cardiac Conduction Delay: A Report of the American College of Cardiology/American Heart Association Task Force on Clinical Practice Guidelines and the Heart Rhythm Society. Circulation. 2019; 140: e382–e482. https://doi.org/10.1161/CIR.0000000000000628.

[2] Gabet A, Lailler G, Fauchier L, Deharo JC, Tuppin P, Leclercq C, et al. Epidemiology of major heart rhythm and conduction disorders. Archives of Cardiovascular Diseases. 2024; 117: 693–704. https://doi.org/10.1016/j.acvd.2024.10.003.

[3] Zhang J, Liu J, Ye M, Zhang M, Yao F, Cheng Y. Incidence and risk factors associated with atrioventricular block in the general population: the atherosclerosis risk in communities study and Cardiovascular Health Study. BMC Cardiovascular Disorders. 2024; 24: 509. https://doi.org/10.1186/s12872-024-04163-9.

[4] Francula-Zaninovic S, Nola IA. Management of Measurable Variable Cardiovascular Disease' Risk Factors. Current Cardiology Reviews. 2018; 14: 153–163. https://doi.org/10.2174/1573403X14666180222102312.

[5] Goorani S, Zangene S, Imig JD. Hypertension: A Continuing Public Healthcare Issue. International Journal of Molecular Sciences. 2024; 26: 123. https://doi.org/10.3390/ijms26010123.

[6] Varvarousis D, Kallistratos M, Poulimenos L, Triantafyllis A, Tsinivizov P, Giannakopoulos A, et al. Cardiac arrhythmias in arterial hypertension. Journal of Clinical Hypertension. 2020; 22: 1371–1378. https://doi.org/10.1111/jch.13989.

[7] Tannenbaum L, Long B. Electrocardiogram essentials: Bradycardia. The American Journal of Emergency Medicine. 2025; 97: 58–64. https://doi.org/10.1016/j.ajem.2025.07.030.

[8] Sabio R, Valdez P, Casariego Vales E, Cámera L, Puello Galarcio HL, Camafort M, et al. Executive summary of the 2025 consensus on the diagnosis and treatment of hypertension of the International Forum on Internal Medicine. Revista Clinica Espanola. 2025; 225: 502368. https://doi.org/10.1016/j.rceng.2025.502368.

[9] Chinese Society of Cardiology, Chinese Medical Association; Hypertension Committee of Cross-Straits Medicine Exchange Association; Cardiovascular Disease Prevention and Rehabilitation Committee, Chinese Association of Rehabilitation Medicine. Clinical practice guideline for the management of hypertension in China. Chinese Medical Journal. 2024; 137: 2907–2952. https://doi.org/10.1097/CM9.0000000000003431.

[10] Ponnusamy SS, Arora V, Namboodiri N, Kumar V, Kapoor A, Vijayaraman P. Left bundle branch pacing: A comprehensive review. Journal of Cardiovascular Electrophysiology. 2020; 31: 2462–2473. https://doi.org/10.1111/jce.14681.

[11] Chow CLD, Wong C, Sutherland N, Obeyesekere MN, Wong GR, Eastwood CM, et al. Clinical Outcomes of Conduction System Pacing vs Right Ventricular Septal Pacing in Atrioventricular Block: The CSPACE Randomized Controlled Trial. Journal of the American College of Cardiology. 2025; 86: 563–573. https://doi.org/10.1016/j.jacc.2025.06.043.

[12] Miyajima K, Urushida T, Tamura T, Masuda S, Okazaki A, Takashima Y, et al. Assessing cardiac mechanical dyssynchrony in left bundle branch area pacing and right ventricular septal pacing using myocardial perfusion scintigraphy in the acute phase of pacemaker implantation. Journal of Cardiovascular Electrophysiology. 2022; 33: 1826–1836. https://doi.org/10.1111/jce.15609.

[13] Liu P, Wang Q, Sun H, Qin X, Zheng Q. Left Bundle Branch Pacing: Current Knowledge and Future Prospects. Frontiers in Cardiovascular Medicine. 2021; 8: 630399. https://doi.org/10.3389/fcvm.2021.630399.

[14] Briongos Figuero S, Estevez Paniagua A, Tapia Martinez M, Jimenez Loeches S, Sanchez Hernandez A, Heredero D, et al. Sustained electrical synchrony with left bundle branch area pacing: results at long-term follow-up. Europace. 2025; 27: euaf085.534. https://doi.org/10.1093/europace/euaf085.534.

[15] Wang JG. Chinese Guidelines for the Prevention and Treatment of Hypertension (2024 revision). Journal of Geriatric Cardiology. 2025; 22: 1–149. https://doi.org/10.26599/1671-5411.2025.01.008.

[16] Haghjoo M. Bradyarrhythmias. In Maleki M, Alizadehasl A, Haghjoo M (eds.) Practical Cardiology (Second Edition) (pp. 289–296). Elsevier: Amsterdam. 2022.

[17] Schaefer J, Schöttler M. The treatment of excessive arterial hypertension by a permanent cardiac pacemaker system: a case report concerning the possibility to influence the disturbed harmonization between the heart and the arterial system (author's transl). Klinische Wochenschrift. 1976; 54: 277–281. https://doi.org/10.1007/BF01468923. (In German)

[18] Gallo G, Savoia C. Hypertension and Heart Failure: From Pathophysiology to Treatment. International Journal of Molecular Sciences. 2024; 25: 6661. https://doi.org/10.3390/ijms25126661.

[19] Masenga SK. Ventricular-Arterial Coupling and Hypertension: Integrating Vascular and Cardiac Indices. American Journal of Hypertension. 2025; 38: 875–877. https://doi.org/10.1093/ajh/hpaf147.

[20] Gao T, Li Z, Li W, Wang X, Xie X. The Risk of New-Onset Atrial Fibrillation in Patients With Conduction System Pacing Versus Right Ventricular Pacing: A Meta-Analysis. Reviews in Cardiovascular Medicine. 2025; 26: 27921. https://doi.org/10.31083/RCM27921.

[21] Li F, Zhang Y, Huang J, Peng SL, Jin MC, Geng C, et al. Lower Risk of New-Onset Atrial Fibrillation in Conduction System Pacing Compared With Right Ventricular Pacing. Pacing and Clinical Electrophysiology. 2025; 48: 202–215. https://doi.org/10.1111/pace.15121.

[22] Harbin MM, Brown CD, Burns KV, Espinoza EA, Dengel DR, Bank AJ. QRS morphology and electrical dyssynchrony in patients before and after cardiac resynchronization therapy and after device optimization. Journal of Electrocardiology. 2025; 92: 154086. https://doi.org/10.1016/j.jelectrocard.2025.154086.

[23] Borgquist R, Marinko S, Platonov PG, Wang L, Chaudhry U, Brandt J, et al. Maximizing QRS duration reduction in contemporary cardiac resynchronization therapy is feasible and shorter QRS duration is associated with better clinical outcome. Journal of Interventional Cardiac Electrophysiology. 2023; 66: 1799–1806. https://doi.org/10.1007/s10840-022-01463-y.

[24] Sales-Belles C, Mincholé A, Melero-Polo J, Cabrera-Ramos M, Vadillo-Martín P, Montilla-Padilla I, et al. ECG-based evaluation of ventricular synchrony in left bundle branch area pacing through characterization of the activation sequence. Scientific Reports. 2025; 15: 15584. https://doi.org/10.1038/s41598-025-98608-6.

[25] Hua W, Fan X, Li X, Niu H, Gu M, Ning X, et al. Comparison of Left Bundle Branch and His Bundle Pacing in Bradycardia Patients. JACC. Clinical Electrophysiology. 2020; 6: 1291–1299. https://doi.org/10.1016/j.jacep.2020.05.008.

[26] Wu X, Hu W, Song L, Chen W, Zhou Y, Zhou L, et al. Use of acoustic cardiography to assess left ventricular electromechanical synchronization during left bundle branch pacing. Heart Rhythm O2. 2023; 4: 632–640. https://doi.org/10.1016/j.hroo.2023.08.009.

[27] Huang J, Guo L, Zhang W, Li R, He B. Left bundle branch potential predicts better electrical synchrony in bradycardia patients receiving left bundle branch pacing. BMC Cardiovascular Disorders. 2022; 22: 376. https://doi.org/10.1186/s12872-022-02812-5.