

ORIGINAL RESEARCH

Cardiac Electrical and Mechanical Synchrony Analysis of LBBP and RVP Utilizing Tissue Doppler Imaging Technology

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ABSTRACT

Background • Right ventricular pacing (RVP) therapy is the conventional approach for atrioventricular block despite its propensity to cause electrical and mechanical dyssynchrony. This dyssynchrony increases the risk of atrial fibrillation and heart failure, eventually leading to left ventricular dysfunction. Left bundle branch pacing (LBBP) has recently emerged as a novel physiological pacing method. This study utilizes conventional ultrasound cardiography (UCG), two-dimensional speckle tracking imaging (2D-STI), and tissue Doppler imaging (TDI) to investigate the disparities in electrical and mechanical cardiac synchrony between LBBP and RVP patients.

Methods • The retrospective analysis includes data from patients who underwent LBBP (n=50) and RVP (n=50) in Zhangjiagang First People's Hospital between January 2019 and June 2020, meeting the stipulated inclusion criteria. The study compares pacing parameters, UCG metrics, cardiac electrical and mechanical synchrony, pacing success rates, and safety events both pre-operation and at 3, 6, 12, and 24 months post-operation.

Results • Implantation success rates for both RVP and LBBP groups were 100%, with 92% and 100% pacing success rates, respectively [$P = .001$ RR (95% CI) : 2.5 (1.5, 3.5)]. The LBBP group exhibited significant advantages over the RVP group throughout the follow-up period.

LBBP patients displayed shortened QRS duration, reduced pacing thresholds and impedance, improved sensory function, lower serum NT-proBNP levels, and an increased proportion of NYHA class I patients [$P = .003$ RR (95% CI) : 1.6 (1.1, 2.3)]. Furthermore, left ventricular ejection fraction increased significantly, while left ventricular diastolic and end-systolic diameters decreased in the LBBP group compared to the RVP group [$P = .004$ RR (95% CI) : 1.7 (1.3, 2.2)]. The LBBP group also demonstrated shorter ventricular systolic synchrony parameters, including Tls-Dif, PSD, Trs-SD, Tas-SD, Tas-post, Ts-SD, and Ts-Dif, compared to the RVP group [$P = .005$ RR (95% CI) : 1.5 (1.2, 2.0)]. Notably, no postoperative complications occurred in either group, such as electrode displacement, lead thrombus attachment, incision bleeding, pocket hemorrhage, or infection. However, the readmission rates for heart failure were 16% in the RVP group and 2% in the LBBP group.

Conclusion • LBBP achieves physiological cardiac pacing, leading to significant improvements in serum NT-proBNP levels and cardiac function and enhanced ventricular contraction synchrony. Utilizing UCG, 2D-STI, and TDI for quantitative evaluation of cardiac electrical and mechanical synchrony proves to be a valuable clinical approach. (*Altern Ther Health Med*. [E-pub ahead of print.])

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INTRODUCTION

Traditional right ventricular pacing (RVP) can lead to left ventricular mechanical dyssynchrony due to prolonged abnormal electrical activation sequences, resulting in heart dysfunction and, in severe cases, cardiogenic death.¹⁻³ His-

bundle pacing (HBP) has emerged as a promising alternative. By directing stimulation along the native conduction system, HBP endeavors to preserve a more physiologically normal electrical activation sequence. This method, in turn, fosters ventricular synchrony and aligns with the principles of true physiological pacing.⁴ Importantly, HBP has demonstrated the capacity to significantly ameliorate QRS duration and enhance left ventricular function, especially among patients grappling with reduced left ventricular ejection fraction (LVEF).^{5,6}

Left bundle branch pacing (LBBP), introduced by Huang et al. in 2017, involves screwing an electrode into the left bundle branch area beneath the left ventricular endocardium. This technique aims to preserve or restore left bundle branch conduction, thereby synchronizing left ventricular

contraction and improving cardiac function.⁷ LBBP offers advantages such as lower pacing thresholds, larger R-wave amplitudes, and a theoretically reduced distal conduction block 8-10 risk. Importantly, LBBP addresses limitations associated with traditional RVP and His-bundle pacing (HBP), demonstrating a remarkable long-term safety profile. This study employs various diagnostic modalities, including conventional ultrasound cardiography (UCG), two-dimensional speckle tracking imaging (2D-STI), and tissue Doppler, to conduct a comparative assessment of clinical outcomes and pacing parameters between RVP and LBBP in the management of conduction block. The objective is to furnish valuable insights for the clinical application of LBBP.

MATERIALS AND METHODS

Participants

This observational study involved 100 patients requiring ventricular pacing who underwent permanent pacemaker implantation in the Cardiology Department of Zhangjiagang First People's Hospital between January 2019 and June 2021. The patient cohort included 56 males and 44 females, aged between 35 and 78 years, with an average age of (65.14±8.31) years. All patients had New York Heart Association cardiac function class (NYHA)¹¹ II or III. The study randomly allocated patients to either the LBBP or RVP groups, each comprising 50 individuals. Inclusion criteria encompassed: (1) Bradyarrhythmia patients meeting the ACC/AHA/HRS guidelines for permanent pacemaker implantation with an expected ventricular pacing ratio of ≥40%; (2) First-time pacemaker implantation; (3) Preoperative cardiac ultrasound confirming a left ventricular ejection fraction >40%; (4) Demonstrated compliance with regular hospital follow-up and postoperative pacemaker programming; (5) Comprehensive understanding by patients and their families of the procedure's necessity, associated risks, informed consent, and signed consent forms. Exclusion criteria included: (1) Physical disabilities, severe musculoskeletal disorders, severe heart failure (NYHA class IV), or profound pulmonary dysfunction hindering normal activities; (2) Severe coronary heart disease (unstable angina, acute myocardial infarction, ischemic cardiomyopathy), significant valvular heart disease, congenital heart anomalies, etc.; (3) Arrhythmia diseases such as persistent atrial fibrillation; (4) Poor sound transmission, precluding satisfactory image acquisition and analysis; (5) Pregnancy; (6) Expected survival of less than 1 year. Ethical clearance for this study was granted by the Institutional Ethics Committee of Zhangjiagang First People's Hospital (Approval No. ZJGYLL—2020—12—LW001).

Electrode implantation method

In the case of transvenous RVP, patients underwent the introduction of the active ventricular electrode through a 7F standard sheath tube. This procedure was conducted via the left axillary vein pathway using the Seldinger method. This particular electrode was equipped with a pre-implanted plastic Stylet wire. The initial positioning of the electrode involved traversing the tricuspid valve within the right ventricular

outflow tract region, followed by retraction to an intermediate location within the right ventricle. Subsequently, the electrode was advanced, in coordination with the Stylet wire, until it reached the correct placement within the mid-septum of the ventricle. This mid-septum position corresponds to the region situated between the right ventricular apex and the annular plane of the atrioventricular valve. Pacing electrocardiograms (ECGs) in leads II, III, and aVF consistently exhibited QRS complexes characterized by an upward or biphasic orientation with relatively narrow QRS durations.

All patients undergoing LBBP procedures received access through the axillary or left subclavian vein using the Seldinger technique. An 8F arterial sheath was carefully inserted, equipped with a hemostatic valve. Utilizing an extended guiding wire, a C315 His-bundle sheath was introduced through the 8F arterial sheath. Under fluoroscopic guidance in both the anterior-posterior and right anterior oblique 30° views, a 3830 active fixation lead (69 cm) from Medtronic Inc., USA, was advanced through the C315 His-bundle sheath. This was done to record and image the His-bundle region for reference. With fluoroscopic guidance in the right anterior oblique 30° view, the sheath and lead were repositioned towards the distal His-bundle region, approximately 1.5 to 2.0 cm from the septum, in a fan-shaped pattern. Pacing measurements and imaging were employed to determine the implantation site, confirming its location within the left bundle branch region. The sheath and lead were then rotated counterclockwise to orient their tips perpendicular to the right ventricular septal surface. The 3830 lead was gradually advanced into the subendocardium of the left bundle branch region. Following the placement of the LBBP lead, a contrast medium was injected through the C315 sheath to assess the position and depth of lead tip insertion into the interventricular septum. During the left bundle branch lead implantation, characteristic changes were observed in the pacing QRS waveform in lead V1. When the lead was positioned within the left bundle branch region, the pacing QRS waveform exhibited characteristics similar to a right bundle branch block (rSr' pattern) in some cases. In certain instances, left bundle branch potentials were recorded, with the left bundle branch potential leading to the onset of surface QRS waves by approximately 20 ms. Postoperatively, transthoracic UCG was performed in multiple positions to observe the depth and location of the active lead, thereby avoiding inadvertent lead tip entry into the left ventricle.

Observation parameters

Preoperative data, including fundamental patient information such as age, were collected, and postoperative follow-up assessments were scheduled at 3 months, 6 months, 12 months, and 24 months. The following data points were meticulously recorded: pacemaker programming pre and post-surgery, UCG parameters, serum N-terminal pro-brain natriuretic peptide (NT-proBNP) levels, intraoperative lead parameters, surgical duration, left ventricular synchrony parameters, heart failure readmissions, and any complications that arose.

Pacemaker programming: Patient-specific ventricular lead pacing, sensing thresholds, and impedances were fine-tuned using the Medtronic 9790 programmer to facilitate the timely adjustment of pacing parameters. Furthermore, the percentages of ventricular pacing were documented.

UCG parameters: The Philips Ie Elite color Doppler ultrasound diagnostic device, equipped with an S5-1 probe operating at a frequency range of 1-5 MHz and integrated with a Qlab 9.1 workstation, was utilized for UCG assessments. During the UCG examination, all patients assumed a left lateral decubitus position while maintaining simultaneous ECG connectivity. Conventional two-dimensional echocardiography was employed to gauge the following cardiac metrics: left atrial diameter (LAD), left ventricular end-diastolic diameter (LVEDD) and left ventricular end-systolic diameter (LVESD). Additionally, the modified biplane Simpson's method facilitated the computation of the left ventricular ejection fraction (LVEF), left atrial area (LAA), left atrial volume (LAV), and left atrial volume index (LAVI), which was standardized according to body surface area. Pulsed-wave Doppler was leveraged to measure early diastolic peak velocity (E-wave) and late diastolic peak velocity (A-wave) at the mitral annulus, with subsequent calculation of the E/A ratio.

NT-proBNP levels: In the morning, a 3 ml fasting venous blood sample was collected from patients. After a low-speed centrifugation process, the supernatant was carefully isolated, and enzyme-linked immunosorbent assay techniques were employed to quantify NT-proBNP levels within the serum.

Heart function classification: The NYHA classification system was utilized to categorize the patients based on their heart function.

2D-STI: STI was conducted by sequentially selecting apical two-chamber, three-chamber, and four-chamber views. Following the activation of automatic functional imaging, automatic endocardial tracing was performed. This process yielded strain-time curves for all 17 myocardial segments within the left ventricle. Parameters extracted included the maximum time-to-peak longitudinal strain difference (Tls-Dif) and peak strain dispersion (PSD) for each segment. The generated images were subsequently transmitted to the Q-Analysis workstation for analysis. Here, measurements included time-to-peak radial strain from the onset of the QRS complex for each segment, time-to-peak radial strain standard deviation (Trs-SD), and the difference in time-to-peak radial strain between the anterior septum and the left ventricular posterior wall during systole (Tas-post).

Tissue Doppler parameters: TDI was performed by sequentially selecting apical two-chamber, three-chamber, and four-chamber views with synchronous imaging. Four sampling points were selected for each section to measure the time-to-peak velocity of myocardial tissue. These measurements calculated the Ts-SD and maximum Ts-Dif velocity for the 12 segments. Left ventricular systolic dyssynchrony was defined as Ts-SD > 32.6 ms.

Complications: The incidence of postoperative complications in both patient groups was compared to assess differences.

Statistical analysis

Data processing was performed utilizing SPSS version 22.0 statistical software. Count data were expressed as frequencies or percentages, and intergroup differences were assessed employing the chi-square test. Measurement data were presented as mean ± standard deviation ($\bar{x} \pm s$), with intergroup differences evaluated via the *t* test. *P* < .05 was considered statistically significant.

RESULTS

Comparison of preoperative baseline characteristics between two patient groups

The preoperative baseline characteristics of the LBBP and RVP groups were compared, and the results are presented in Table 1. The analysis revealed no significant differences between the two groups in gender, age, body surface area, serum NT-proBNP levels, and baseline QRS duration (*P* > .05).

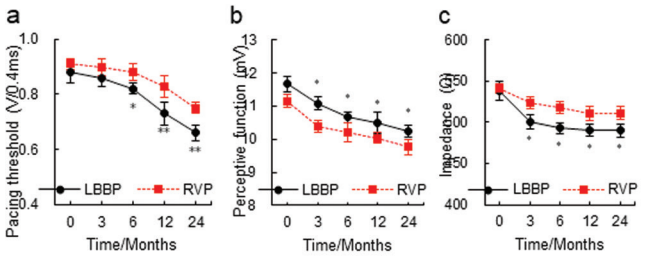
Comparison of pacing parameters before and after treatment between two patient groups

Comparisons were conducted on pacing parameters of patients in both the LBBP and RVP groups at intraoperative and postoperative intervals of 3, 6, 12, and 24 months (refer to Figure 1). There were no notable disparities in pacing threshold and impedance during surgery between the LBBP and RVP

Table 1. Comparison of preoperative baseline characteristics.

Material	LBBP group	RVP group	χ^2 or <i>t</i>	<i>P</i> value
Sample size	50	50		
Male (case/%)	30/60.0	26/52.0	0.155	.790
age	60.32±8.58	61.60±7.23	0.097	.884
Body surface area (m ²)	1.65±0.14	1.69±0.15	0.128	.796
Blood NT-proBNP (ng/l)	923.43±36.77	956.74±40.28	0.034	.852
Basic QRS time limit (ms)	110.59±5.15	108.35±5.89	0.367	.343
Comorbidities			0.982	.452
DM	46%	45%		
HTN	55%	56%		
CAD	46%	45%		
Echocardiography LVEF (%)	60.2 ± 4.8	59.3 ± 5.7	0.578	.321

Figure 1. Comparison of pacing parameters between the two groups ($\bar{x} \pm s$). (a) pacing threshold; (b) sensing function; (c) the impedance

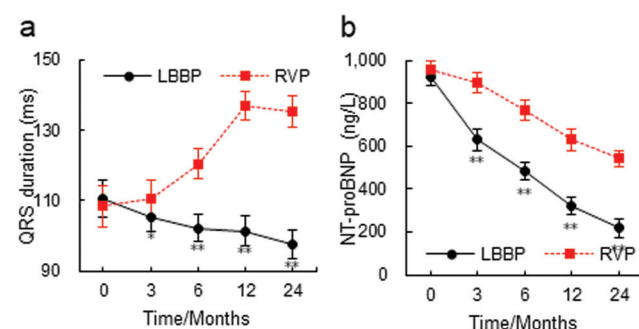


Note: results at 0 months represent intraoperative measurements, while results at 3 to 24 months represent postoperative follow-up measurements; in comparison to the RVP group, **P* < .05, ***P* < .01.

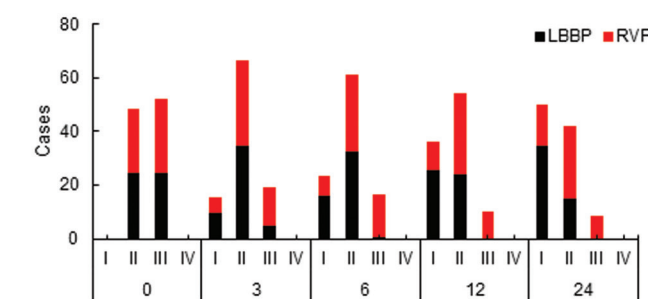
Table 2. Comparison of UCG parameters between two groups ($\bar{x} \pm s$)

Group	LAD (mm)	LVEDD (mm)	LVESD (mm)	LVEF (%)	LAA (cm ²)	LAV (ml)	LAVI (ml/m ²)	E/A
LBBP group								
Preoperative baseline	39.75±4.14	52.15±4.51	34.46±2.19	51.37±3.36	19.33±1.63	55.67±3.94	34.87±2.81	0.95±0.25
3 months after surgery	37.98±4.82	50.23±3.86	33.64±3.62	53.92±3.92	20.78±2.03	56.82±2.98	35.27±3.96	1.14±0.34
6 months after surgery	37.28±3.89	50.60±4.08	33.43±3.33	54.03±4.77	21.68±1.77	57.33±4.78	36.03±3.72	1.28±0.21
12 months after surgery	36.49±3.65	49.78±4.73	32.85±2.18	55.72±4.72	22.76±1.84	57.82±4.22	37.13±2.66	1.35±0.22
24 months after surgery	35.67±3.93	49.23±4.82	31.77±2.63	56.38±4.62	22.95±1.42	58.72±3.94	37.92±2.13	1.63±0.30
RVP group								
Preoperative baseline	38.52±3.88	51.59±4.07	34.60±2.25	52.74±2.89	19.69±1.83	55.82±2.93	34.92±2.48	1.09±0.25
3 months after surgery	39.72±3.72	52.13±3.65*	35.86±3.51*	51.82±4.33	21.78±2.37*	60.72±3.81*	36.82±2.63*	0.94±0.23*
6 months after surgery	39.45±3.65*	52.21±4.78*	35.75±2.98*	50.93±4.82*	22.43±2.04*	61.87±4.42*	37.92±2.58*	0.87±0.29*
12 months after surgery	40.22±4.64*	53.45±4.51*	37.54±2.73*	49.67±3.19*	23.68±1.93*	62.35±3.85*	38.99±2.75*	0.83±0.27*
24 months after surgery	41.28±3.85*	55.98±4.92*	38.73±3.05*	48.11±3.73*	23.92±1.57*	63.83±3.98*	39.62±2.83*	0.75±0.25*

*Comparison to the RVP group, $P < .05$.

Figure 2. Comparison of QRS duration and NT-proBNP levels between the two groups. (a) QRS duration; (b) blood NT-proBNP levels


Note: 0 months denote intraoperative measurements, while 3~24 months represent postoperative follow-up months; in comparison to the RVP group, * $P < .05$, ** $P < .01$.

Figure 3. Comparison of postoperative cardiac functional classification between the two groups [Cases (%)].


groups ($P > .05$). Throughout the postoperative follow-up period, both groups displayed varying degrees of improvement in pacing threshold, sensing function, and impedance. Compared to the RVP group, the LBBP group exhibited significantly lower pacing thresholds and impedances, along with notably higher sensing function ($P < .05$).

Comparison of UCG parameters between two groups of patients before and after treatment

The UCG parameters between the LBBP and RVP groups were compared before the operation and at 3, 6, 12, and 24 months postoperatively (Table 2). Before the operation, there were no significant differences in LAD, LVEDD, LVESD, LVEF, LAA, LAV, LAVI, and E/A parameters

between the LBBP and RVP groups ($P > .05$). During postoperative follow-up, LAD, LVEDD, LVESD, LAA, LAV, LAVI, LVEF, and E/A levels in the LBBP group exhibited varying degrees of reduction. In contrast, the RVP group showed varying degrees of increase in LAD, LVEDD, LVESD, LAA, LAV, and LAVI levels, alongside decreased LVEF and E/A ratios. Significantly smaller LAD, LVEDD, LVESD, LAA, LAV, LAVI, higher LVEF, and E/A were observed in the LBBP group compared to the RVP group postoperatively ($P < .05$).

Comparison of QRS duration, blood NT-proBNP, and cardiac functional classification before and after treatment in two groups

Comparisons were conducted between the LBBP and RVP groups concerning QRS duration and blood NT-proBNP levels before and after treatment at 3, 6, 12, and 24 months (Figure 2). No significant differences were found in baseline QRS duration and blood NT-proBNP levels between the LBBP and RVP groups, consistent with Table 1 ($P > .05$). During postoperative follow-up, the LBBP group displayed a decrease in QRS duration compared to baseline, while the RVP group exhibited a gradual increase. Both groups showed a progressive decrease in serum NT-proBNP levels after surgery. In comparison to the RVP group, the LBBP group had significantly lower QRS duration and blood NT-proBNP levels after treatment ($P < .05$).

A comparative analysis was conducted between the LBBP and RVP groups regarding differences in NYHA cardiac functional classification before and after treatment at 3, 6, 12, and 24 months (Figure 3). Preoperatively (0 months), both groups exhibited NYHA cardiac functional classifications of either II or III. However, at 3, 6, 12, and 24 months post-surgery, the LBBP group had a significantly higher number of individuals classified as NYHA functional class I compared to the RVP group. Moreover, at 12 and 24 months after surgery, no individuals in the LBBP group were classified as NYHA functional class III. In contrast, the RVP group had 10 and 8 individuals in this category, respectively.

Comparison of left ventricular mechanical synchrony before and after treatment in two groups

A comprehensive analysis was carried out to compare left ventricular mechanical synchrony parameters between the LBBP group and the RVP group before and after

Table 3. Comparison of left ventricular synchrony parameters in two groups ($\bar{x} \pm s$)

Group	Tls-Dif (ms)	PSD (ms)	Trs-SD (ms)	Tas-post (ms)	Ts-SD	Ts-Dif (ms)	Tls-Dif (ms)	PSD (ms)
LBBP group								
Preoperative baseline	150.82±24.98	40.33±6.78	70.35±7.95	138.83±4.66	36.92±3.97	80.33±7.54	150.82±24.98	40.33±6.78
3 months after surgery	157.68±26.83	45.89±7.56	78.99±6.96	97.82±5.75	31.82±3.86	90.03±7.93	157.68±26.83	45.89±7.56
6 months after surgery	159.38±34.82	47.29±6.63	83.29±7.74	88.93±4.87	30.75±4.84	98.37±8.85	159.38±34.82	47.29±6.63
12 months after surgery	168.92±29.73	49.44±7.76	93.92±7.93	77.17±5.75	28.73±3.97	105.74±6.92	168.92±29.73	49.44±7.76
24 months after surgery	189.77±33.25	50.82±5.96	109.24±6.83	68.72±4.87	26.61±4.96	118.64±7.94	189.77±33.25	50.82±5.96
RVP group								
Preoperative baseline	189.26±26.86 ^a	48.28±6.97 ^a	82.66±7.97 ^a	135.33±5.86 ^a	35.99±4.86 ^a	89.41±7.28 ^a	189.26±26.86 ^a	48.28±6.97 ^a
3 months after surgery	237.85±32.86 ^a	59.29±7.73 ^a	118.92±7.38 ^a	130.82±4.83 ^a	30.93±4.95 ^a	134.82±7.93 ^a	237.85±32.86 ^a	59.29±7.73 ^a
6 months after surgery	253.73±28.54 ^a	67.52±7.32 ^a	127.83±7.84 ^a	129.92±5.93 ^a	33.22±5.96 ^a	139.74±6.82 ^a	253.73±28.54 ^a	67.52±7.32 ^a
12 months after surgery	283.82±28.39 ^a	70.82±7.84 ^a	131.82±6.94 ^a	120.69±6.05 ^a	40.59±5.35 ^a	146.86±6.84 ^a	283.82±28.39 ^a	70.82±7.84 ^a
24 months after surgery	289.67±25.86 ^a	72.93±7.94 ^a	131.97±6.93 ^a	118.72±5.43 ^a	45.74±5.74 ^a	149.74±7.93 ^a	289.67±25.86 ^a	72.93±7.94 ^a

^aComparison to the RVP group, $P < .05$.

treatment at 3, 6, 12, and 24 months (Table 3). Before surgery, there were no noteworthy disparities in Tls-Dif, PSD, Trs-SD, Tas-SD, and Ts-Dif parameters between the LBBP and RVP groups ($P > .05$), aligning with the findings in Table 1. However, during postoperative follow-up, both groups exhibited varying degrees of increases in Tls-Dif, PSD, Trs-SD, Tas-SD, and Ts-Dif. In contrast, the LBBP group notably reduced Ts-post and Ts-SD. In contrast to the RVP group, the LBBP group demonstrated significantly lower values in Tls-Dif, PSD, Trs-SD, Tas-SD, Tas-post, Ts-SD, and Ts-Dif after surgery ($P < .05$).

The evaluation of left ventricular synchrony status in the LBBP and RVP groups employed a bull's eye map based on 18-segment Tls (Figure 4). During the selective LBBP procedure within the LBBP group, the bull's eye map displayed minimal color variation, predominantly appearing in shades of green or yellow-green. Tls across the left ventricular's 18 segments ranged from 315 to 330 ms, indicating a favorable left ventricular synchrony status in these patients (Figure 4a). Conversely, in the RVP group, during pacing, the bull's eye map exhibited chaotic colors, with a noticeable decrease in green regions, and some segments displayed shades of orange or red. Tls within the left ventricular's 18 segments ranged from 330 to 500 ms, suggesting an unfavorable left ventricular synchrony status in these patients (Figure 4b).

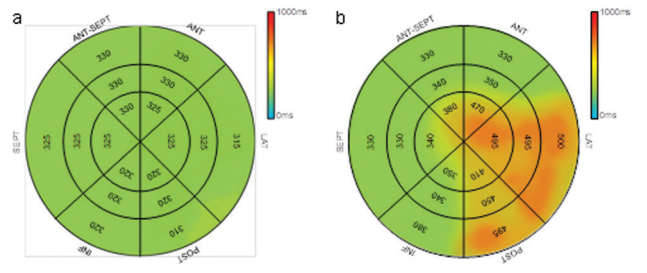
Clinical outcomes in two groups

In the context of clinical outcomes, both the LBBP and the RVP groups achieved a 100.0% success rate for implantation. However, concerning pacing success, the LBBP group achieved a 100.0% success rate, while the RVP group had a slightly lower success rate of 92.0%. Throughout the follow-up period, neither group encountered postoperative complications such as electrode displacement, lead thrombosis, incisional hemorrhage, pericardial hematoma, or infection. Regarding heart failure readmission, it was observed that 1 case (2.0%) in the LBBP group and 8 cases (16.0%) in the RVP group were readmitted due to heart failure.

DISCUSSION

Recent research has substantiated the detrimental effects of prolonged RVP, which can lead to intraventricular and interventricular dyssynchrony.¹²⁻¹⁴ Normally, cardiac pacing

Figure 4. Bull's-eye diagram of Tls at systolic segment 18 of the left ventricle after pacing (a) the Tls of the 18th segment of the left ventricle during LBBP ranges from 315 to 330 ms, showing good left ventricular synchronization; (b) the Tls of the 18th segment of the left ventricle during RVP ranges from 330 to 500 ms, showing poor left ventricular synchronization.



originates from the sinus node P-cells, generating electrical excitation and propagating through the atria's conduction pathway to the atrioventricular node. From there, it traverses the His-Purkinje fiber system to induce excitation and contraction of the heart.¹⁵ The His-Purkinje fiber system plays a pivotal role in cardiac conduction, efficiently transmitting electrical impulses from the sinus node to the ventricles. HBP utilizes the inherent His-Purkinje fiber system for synchronous ventricular contractions. In contrast, LBBP bypasses pathological or vulnerable conduction regions, achieving true conduction system pacing by directly stimulating the His-Purkinje fiber system.^{16,17} LBBP offers direct stimulation of the His-Purkinje fiber system, circumventing the disadvantages linked to premature ventricular muscle activation observed in traditional RVP. Consequently, LBBP achieves electrical conduction that closely mimics the physiological state.¹⁸ Previous studies have endorsed HBP as a primary treatment for heart failure patients with left ventricular dyssynchrony,¹⁹ and recent research demonstrates the effectiveness of LBBP in heart failure patients with bundle branch block.²⁰ LBBP primarily activates the left ventricle through the His Bundle-Purkinje fiber system, thereby reducing the extent of left ventricular asynchrony. Compared to HBP, LBBP offers stable and lower capture thresholds, particularly in patients with distal His bundle conduction disease.²¹⁻²³ Throughout this study, both LBBP and RVP groups exhibited reductions in pacing thresholds and impedance values during follow-up. However, the LBBP group consistently demonstrated lower pacing

thresholds and impedances than the RVP group, indicating enhanced sensing capabilities. Lower pacing thresholds imply that lower electrical stimulus intensity is required for effective pacing.²⁴ Reduced impedance signifies improved electrical signal transmission through cardiac tissue, enhancing pacing efficacy.²⁵ Pacemakers often incorporate sensing capabilities to detect intrinsic heart electrical activity. Enhanced sensing capabilities indicate the pacemaker's improved ability to identify the natural heart rate and adjust pacing modes accordingly.²⁶ This study's findings suggest that LBBP offers lower pacing thresholds, superior sensing capabilities, and stable impedances. Nonetheless, it is important to note that lead insulation breakdown or intracavitary lead displacement may decrease pacing impedance.²⁷ Given the study's relatively small sample size, further research is needed to explore the impact of LBBP and RVP treatments on pacing parameters.

In physiological circumstances, the ventricles' pacing actions on both sides of the heart occur almost simultaneously, resulting in a narrow and typical QRS wave. QRS duration serves as an indicator reflecting the synchrony of myocardial electrical activity.^{28,29} This study observed that QRS duration in the LBBP group was notably shorter than in the RVP group. This result confirms superior electrical synchronization in the LBBP group compared to the RVP group. RVP can lead to delayed activation of the left ventricular free wall and lateral wall, inducing myocardial electrical dyssynchrony.³⁰ Consequently, RVP is linked to a higher incidence of clinical adverse events such as heart failure, atrial fibrillation, and pacemaker-induced cardiomyopathy. The rapid conduction velocity of the His Bundle-Purkinje fiber system may result in swift retrograde activation of the right bundle branch, consequently shortening the duration of the QRS wave in the LBBP group.³¹ Yu et al. revealed that roughly 74% of patients with chronic heart failure and QRS prolongation exhibit left ventricular dyssynchrony. Additionally, even 51% of patients with chronic heart failure and normal QRS duration display left ventricular dyssynchrony.³² Molhoek et al. posited that QRS duration primarily reflects the synchrony of myocardial electrical activity and serves as an indirect indicator of left ventricular systolic dyssynchrony. Mechanical dyssynchrony is the direct metric for assessing left ventricular systolic synchrony in patients.³³ Through LBBP therapy, the left bundle branch's conduction function can be restored, resulting in more synchronous pacing actions on both sides of the ventricles. Consequently, QRS duration diminishes, transforming the wide and aberrant QRS complex into a narrower form that tends towards a typical QRS waveform.³⁴ This positive outcome of LBBP treatment signifies an improvement in ventricular electrical activity, potentially correlating with enhanced cardiac function in treated patients.

In heart failure patients, BNP swiftly and specifically expresses in response to ventricular wall stress, with its level closely linked to this stress. BNP primarily originates in the heart as proBNP, a precursor molecule. Enzymatic cleavage of proBNP yields biologically active BNP and an N-terminal

fragment, NT-proBNP.³⁵ In comparison to BNP, NT-proBNP boasts an extended half-life and superior diagnostic specificity for heart failure.³⁶ This study investigated RVP and LBBP groups, revealing a consistent reduction in serum NT-proBNP levels post-pacing compared to baseline. Intriguingly, the LBBP group exhibited significantly lower NT-proBNP levels than the RVP group, aligning with a notably lower NYHA functional class in the LBBP group. These outcomes underscore LBBP's potential to lower serum NT-proBNP levels in patients, suggesting a substantial contribution to enhanced cardiac function. Moreover, NT-proBNP stands as a valuable predictive marker for post-implantation heart failure following cardiac pacemaker procedures.

Assessing cardiac motion synchrony is crucial in the management of heart-related conditions. Common methods for evaluating cardiac motion synchrony encompass cardiac Magnetic Resonance Imaging, UCG, and multi-gated blood pool fluorescence imaging. UCG stands out due to its non-radioactive nature and real-time monitoring capabilities, allowing for precise measurements of left ventricular ejection fraction and cardiac motion synchrony.³⁷ LBBP is an emerging physiological pacing method, primarily under exploration in clinical feasibility and safety assessments in China. Advanced ultrasound techniques, notably 2D-STI and TDI, offer non-invasive, quantitative, and repeatable means to assess left ventricular mechanical contraction synchrony.³⁸ While no universally recognized "gold standard" exists for evaluating ventricular mechanical contraction synchrony, 2D-STI analyzes myocardial tissue motion by tracking speckle position changes over time, enabling quantitative assessments of myocardial contraction synchrony.^{39,40} TDI is a well-established ultrasound technique designed to measure the velocity and displacement of myocardial tissue during both the contraction and relaxation phases.⁴¹ It offers a quantitative approach to analyzing mechanical motion parameters within specific ventricular segments. This method generates high-temporal-resolution velocity-time curves, providing clear and reproducible measurement results. These curves offer a detailed representation of the onset and dispersion of myocardial mechanical motion.⁴² This study investigated the impact of LBBP on left ventricular mechanical synchrony, comparing it with RVP. The mechanical coupling process of myocardial electrical excitability across various atrial, ventricular, and interventricular segments is visualized by employing the TDI technique in conjunction with surface ECG. The results reveal that LBBP significantly reduced parameters such as TIs-Dif, PSD, Trs-SD, Tas-SD, Tas-post, Ts-SD, and Ts-Dif in comparison to the RVP group. These findings underscore the ability of LBBP to enhance left ventricular mechanical synchrony. Moreover, this study aligns with previous research by Schmidt et al., which demonstrated substantial prolongation of LVPT in patients with RVP and LBBP.⁴³ This study explored the potential benefits of LBBP compared to RVP in achieving enhanced left ventricular mechanical synchrony. LBBP closely replicates physiological conduction, while RVP can induce left

ventricular contraction asynchrony. In a study by Hou et al., the safety and efficacy of permanent LBBP therapy for bradycardia were evaluated, demonstrating favorable electrocardiographic and left ventricular mechanical synchrony outcomes.⁴⁴ To assess left ventricular contraction synchrony, the study implemented specific criteria using Tas-post ≥ 130.0 ms and Ts-SD ≥ 32.6 ms. Results revealed that the LBBP group consistently maintained Tas-post < 130.0 ms and Ts-SD < 32.6 ms post-implantation, indicating successful left ventricular contraction synchrony. Conversely, the RVP group showed Ts-post < 130.0 ms immediately after implantation, but Ts-SD exceeded 32.6 ms at the 12-month, suggesting potential long-term left ventricular contraction asynchronously induced by RVP.

This study delves into the potential of LBBP to improve pacing success rates and safety compared to traditional leads with retractable screws. Barba-Pichardo et al. reported success rates of 35.4% and 71.4% for HBP pacing in patients with supra-Hisian conduction block and conduction block, respectively.⁴⁵ Liu et al. demonstrated that RVP can induce electrical and mechanical dyssynchrony, elevating the risk of arrhythmias and heart failure. Conversely, LBBP exhibits a lower complication rate and higher success rate.⁴⁶ Su et al. conducted an extensive assessment of LBBP in 632 patients from diverse groups, revealing an impressive success rate of 97.8%. They observed a few cases of permanent right bundle branch injury, bundle capture loss, or high capture thresholds. Some patients required lead revisions due to displacement.⁴⁷ In this study, the LBBP group achieved a pacing success rate of 100.0%. However, the influence of the relatively small sample size on this result should be considered. Future research should incorporate larger sample sizes to comprehensively analyze factors impacting LBBP pacing success rates. Sharma et al. compared adverse outcomes, including all-cause mortality, heart failure readmissions, or dual-chamber pacing, in patients with LBBP and RVP pacemaker implants. They noted adverse event rates of 10.0% in the LBBP group and 23.3% in the RVP group, with lower mortality in LBBP patients.⁴⁸

In this study, heart failure readmission rates were 16.0% in the LBBP group and 2.0% in the RVP group, accompanied by significant differences in other complications. Consequently, further investigations are essential to comprehensively assess the safety of LBBP and compare its effectiveness and safety with other pacing modalities.

Left bundle branch pacing (LBBP) offers unique advantages and potential drawbacks when compared to other pacing modalities, such as His-Bundle Pacing (HBP) and traditional right ventricular pacing (RVP). Advantages of LBBP over HBP and RVP: (1) Preservation of physiological activation sequence: LBBP aims to preserve or restore left bundle branch conduction, resulting in a more physiological activation sequence than HBP and RVP. By stimulating the left bundle branch area, LBBP promotes left ventricular contraction synchrony and improves cardiac function. (2) Lower pacing thresholds and larger R-wave amplitudes:

LBBP has been shown to have lower pacing thresholds and larger R-wave amplitudes compared to HBP and RVP. This may contribute to more effective and reliable pacing, ensuring optimal electrical activation of the ventricles. (3) Reduced risk of distal conduction block: LBBP theoretically carries a reduced risk of distal conduction block compared to HBP. By targeting the left bundle branch area, LBBP may overcome some limitations associated with traditional pacing methods and minimize the risk of conduction disturbances. (4) Long-term safety profile: LBBP has demonstrated a remarkable long-term safety profile. The study mentioned in the document did not observe any postoperative complications in the LBBP group. This suggests that LBBP is a safe procedure with a low risk of complications. Potential drawbacks of LBBP: (1) Technical challenges and expertise: LBBP is a technically challenging procedure that requires specialized skills and expertise. The precise placement of the pacing electrode in the left bundle branch area can be difficult, and there is a learning curve associated with performing LBBP. This may limit the widespread adoption of LBBP and the availability of experienced operators. (2) Limited clinical evidence: Although LBBP has shown promising results in several studies, including the one mentioned in the document, the clinical evidence supporting its long-term efficacy and outcomes is still relatively limited compared to HBP and RVP. Further research and larger-scale studies are needed to validate the benefits of LBBP and assess its long-term effects. (3) Procedural complexity and time consumption: LBBP is a more complex procedure than RVP, requiring additional time and resources. The placement of the pacing electrode in the left bundle branch area involves more intricate steps and may require advanced imaging techniques for accurate localization. This can increase procedural time and potentially limit its widespread adoption. (4) The findings of the study provide valuable insights into the advantages of left bundle branch pacing (LBBP) compared to traditional right ventricular pacing (RVP) in the management of conduction block. Firstly, the study observed a higher pacing success rate of 100% in the LBBP group compared to 92% in the RVP group. This indicates that LBBP is a reliable and effective pacing method, ensuring proper electrical activation of the ventricles. Improved pacing success rates are crucial for maintaining optimal heart function and reducing the risk of complications. Secondly, the study demonstrated that LBBP patients exhibited several improvements in cardiac function and electrical synchrony compared to RVP patients. LBBP was associated with shortened QRS duration, reduced pacing thresholds and impedance, and improved sensory function. These findings suggest that LBBP can achieve better electrical synchrony, leading to more efficient ventricular contractions and improved overall cardiac performance. Furthermore, the LBBP group showed significant improvements in serum NT-proBNP levels, a marker of heart failure, as well as an increased proportion of patients in NYHA class I, indicating better functional status. Additionally, left ventricular ejection

fraction increased significantly in the LBBP group, while left ventricular diastolic and end-systolic diameters decreased compared to the RVP group. These findings suggest that LBBP can improve cardiac function and reverse left ventricular dysfunction. Another important outcome observed in the study was the absence of postoperative complications in both the LBBP and RVP groups. This indicates that LBBP is a safe procedure with a low risk of complications, such as electrode displacement, lead thrombus attachment, bleeding, or infection. The lower readmission rates for heart failure in the LBBP group further highlight the potential of LBBP to reduce the risk of heart failure-related complications.

In summary, LBBP emerges as a compelling option to fulfill patients' physiological pacing requirements. LBBP not only leads to notable enhancements in serum NT-proBNP levels and cardiac function but also achieves superior cardiac electrical and mechanical synchrony compared to RVP. These findings underscore the potential of LBBP as an advantageous pacing technique.

Limitations

The study has several limitations that should be acknowledged. One of the main limitations is the relatively small sample size of the LBBP and RVP groups ($n=50$ each). A small sample size can limit the statistical power and generalizability of the findings. The results may not fully represent the broader population of patients undergoing LBBP or RVP. Therefore, caution should be exercised when extrapolating these findings to larger populations. Another potential limitation is the study's retrospective nature, which may introduce selection bias. The inclusion criteria for the study were not explicitly mentioned, and there might have been inherent biases in selecting patients who underwent LBBP or RVP. This could affect the generalizability of the results to a broader population. A prospective, randomized, controlled trial with a larger sample size and well-defined inclusion criteria would provide more robust evidence. Additionally, although the study utilized various diagnostic modalities (UCG, 2D-STI, and TDI) to evaluate cardiac electrical and mechanical synchrony, there may be other advanced imaging techniques or parameters that were not considered. Incorporating additional imaging modalities or exploring other synchrony parameters could provide a more comprehensive understanding of the differences between LBBP and RVP.

Future research should aim to address these limitations by conducting larger-scale prospective studies with well-defined inclusion criteria. Randomized controlled trials comparing LBBP, HBP, and RVP would allow for more accurate comparisons and provide stronger evidence regarding the benefits and drawbacks of each pacing modality. Long-term follow-up assessments are also needed to evaluate the durability of the observed improvements and assess the impact on patient outcomes, including quality of life, heart failure management, and survival rates. Furthermore,

incorporating more advanced imaging techniques, such as three-dimensional echocardiography or cardiac magnetic resonance imaging, may provide additional insights into the mechanisms and effects of LBBP. Exploring other parameters of cardiac electrical and mechanical synchrony could further enhance our understanding of the benefits of LBBP and its potential advantages over other pacing modalities.

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