Occurrence of ventricular septal perforation in patients with permanent left bundle branch pacing followed up using echocardiographic and computed tomography images

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Abstract
Objective: To explore short-term changes after left bundle branch pacing (LBBP) using echocardiography and computed tomography (CT), especially for postoperative ventricular septal perforation.

Methods: Between January and September 2019, 33 patients with atrioventricular block underwent LBBP at Beijing Anzhen Hospital. All the patients were evaluated using electrocardiography, pacing, parameters and echocardiographic measurements, including for major complications, during the 1, 3, 6, 12 and 24-month follow-up. Interval perforations were examined during a 1-month follow-up echocardiogram and CT.

Results: Left bundle branch pacing was successfully performed in 100% (33/33) of patients. The mean seizure threshold was stable and unchanged postoperatively at the 1, 3, 6, 12 and 24-month follow-up. The paced QRS duration of the LBBP was 119.72 ± 2.53 ms and <130 ms in all patients. Unipolar impedance during the procedure was higher than 500 Ω (662.00 ± 181.50 Ω). No ventricular septal perforation occurred at the end of the procedure. At the 1-month follow-up, two patients reported transthoracic echocardiography, with CT revealing septal lead perforation. Through CT, two other patients were found to have septal lead perforation, and echocardiography indicated that the pacing lead had penetrated the interventricular septum and entered the left subendocardium. At the 1, 3, 6, 12 and 24-month follow-up, these four patients exhibited no significant increase in pacing threshold or impedance (p > .05). No ventricular thrombus or stroke was detected.

Conclusion: Permanent LBBP is safe and feasible in patients with bradycardia. Echocardiography and/or CT can more accurately evaluate changes in cardiac structure and function after LBBP.

Keywords
atrioventricular block, complication, computed tomography scan, echocardiographic, left bundle branch pacing, septal perforation

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1 | INTRODUCTION

Recently, selective Hastelloy bundle pacing (S-HBP) and nonselective Hastelloy bundle pacing (NS-HBP) have become pacing strategy options for restoring the normal driving sequence and reducing atrial fibrillation, pacing-induced cardiomyopathy and heart failure complications. (Andersen et al., 1997; Cho et al., 2019; Khurshid et al., 2014; Lamas et al., 2002; Sweeney et al., 2003; Vijayaraman et al., 2017, 2018) However, S-HBP and NS-HBP remain unpopular because of the increased pacing thresholds during follow-up and the technical difficulty of the procedure. (Barba-Pichardo et al., 2010; Vijayaraman et al., 2017; Vijayaraman et al., 2015)

Huang reported left bundle branch pacing (LBBP) using the 3830 lead in a patient with left bundle branch block (LBBB) and heart failure. (Huang et al., 2019) The study revealed that LBBP could restore left ventricular function and correct LBBB. In addition, Chen reported that LBBP produced a narrow QRS duration and low pacing threshold in 20 patients. (Chen et al., 2019) demonstrating that LBBP could restore left ventricular function and correct LBBB. The left bundle branches into three interconnected bundles that pass posteriorly and inferiorly through the central fiber body into the ventricular cusp. (Elizari, 2017) LBBP achieves a lower and stable output compared with S-HBP and NS-HBP. Since the distance from the end of the anode ring to the tip of the 3830 lead is 14.6 mm, which is much larger than the average thickness of the interventricular septum (IVS), septal perforation remains one of the main problems in LBBP. (Huang et al., 2017) Huang suggested that a unipolar pacing impedance above 500Ω during the procedure was helpful to avoid septal perforation. (Huang et al., 2019) However, this study, which evaluated the lead position and potential lead perforation of the ventricular septum, was limited.

Therefore, the objectives of our study were to (1) Follow dynamic changes in LBBP sensing and pacing thresholds and (2) Observe the lead position and potential septal perforation using electrophysiological recording and computed tomography (CT).

2 | METHODS

2.1 | Study subjects

Thirty-three consecutive patients with atrioventricular block (AVB) receiving treatment at Beijing Anzhen Hospital between January and September 2019 were studied. All the patients had an indication for ventricular pacing according to the 2013 European Society of Cardiology guidelines for cardiac pacing. (Brignole et al., 2013) Exclusion criteria: (1) A transthoracic echocardiographic assessment of a left ventricular (LV) ejection fraction (LVEF) of less than 55%; (2) A previous implantation of any cardiac device; (3) Persistent atrial fibrillation. Our study was approved by the institutional review board of the Beijing Anzhen Hospital, and all the patients gave their written informed consent for the implantation procedure.

2.2 | LBBP procedure

In line with the method described by Huang (Huang et al., 2019), the sheath was fixed using a curved sheath (C315 His, Medtronic). Select Secure pacing leads (Model 3830, 69 cm, Medtronic) were delivered for implantation through the left axillary or left subclavian veins (Figure 1a). The sheath was advanced through the tricuspid annulus, and a pacing lead was introduced transvenously into the right ventricle and screwed into the IVS. A schematic of LBBP is presented in Figure S1. An electrophysiological recording system (CARTO system, Biosense Webster) was used, and an intracardiac electrogam was recorded from the lead tip.

After measuring the hippocampal potential, the ventricular lead (V1) was moved to the middle or base of the IVS to find the hippocampal potential (Figure 1e). After recording the His potential from the lead tip, V1 was tightened until its morphology presented as a “W” with an intermediate notch at the 45° left anterior oblique (LAO) position (Figure 1f). V1 was then rotated 4–6 times clockwise. Thus, the notch in V1 migrated towards the end of the QRS (Figure 1g, Figure 1h). LBBP was successful because of the unipolar paced QRS with the right BBB (RBBB)-like morphology (QR or rSR morphology in V1, and the presence of 5 waves in leads V5 and V6), and paced QRSd leads larger than 130 ms (Figure 1f, Figure 1i). Pacing threshold testing was performed during the procedure to avoid lead dislodgement and septal perforation. The V1 position was determined at the 45° LAO position (Figure 1c) and the 30° right anterior oblique (RAO) position (Figure 1d). LV septal pacing was also accepted because of the relatively narrow QRSd if left bundle potentials could not be recorded after five attempts of electrode positioning or after a fluoroscopy duration of more than 20 min. (Mafi-Rad et al., 2016)

2.3 | Echocardiography

Transthoracic echocardiography was performed to detect the 3830 leads in the IVS following the pacemaker implantation. The depth was measured from the lead entrance of the right ventricular septum to the end of the lead tip to determine whether the lead tip had penetrated the ventricular septum. The distance between the tricuspid septum and ventricular leads was measured using a standard 4-chamber view (Figure 1b). Other parameters, such as the LV end-diastolic diameter (LVEDD), LVEF, and IVS thickness, were obtained before LBBP.

2.4 | Follow-up

Lead parameters, such as the pacing threshold, R-wave amplitude, and unipolar pacing impedance, were measured during the operation, before discharge and at the 1, 3, 6, 12 and 24-month follow-up. During the 1-month follow-up, CT and echocardiography were performed to determine the location of the ventricular leads.
The data were analyzed using SPSS 24.0 (IBM). The Kolmogorov–Smirnov test was used to test the normality of continuous variables, and the Levene test was used to test the homogeneity of variance. Normal distribution measurement data are expressed as mean ± standard deviation (±s), and non-normal distribution measurement data are expressed as median and quartile spacing. The two independent samples t-test (data obey normal distribution) or two independent samples nonparametric test (data do not obey normal distribution) were used for the comparison between the two groups. Count data are expressed as a percentage (%). p < .05 indicated that the difference was statistically significant.
The mean IVS thickness was 10.08 ± 0.40 mm. Other baseline characteristics are shown in Table 1.

3.2 | Electrocardiogram characteristics and lead parameters

Left bundle branch pacing was successfully achieved in all patients. The stenotic endocardial pacing QRSd (<130 ms) or paced QRS morphology with intermediate notching in the V1 lead was recorded in these patients (93.9%). However, left bundle branch potentials were recorded in only 30.3% (10/33) of patients with LBBP. At 3.0 V/0.4 ms, the average pacing QRSd was 119.72 ± 2.53 ms, and the mean R-wave after the LBBP procedure was 14.00 ± 1.47 mV. The lead parameters during the LBBP procedure are presented in Table 2. In all the LBBP parameters, the QRS complex narrowed significantly in both the right and left BBB. Even if the QRSd was abnormal at baseline, the post-LBBP procedure QRSd was still <130 ms. For patients with complete RBBB, QRS was corrected at an output of 3.0 V/0.4 ms by 109 ms of the LBBP in the V1 lead (Figure 2a,b).

For patients with complete LBBB, the baseline QRSd of 182 ms (Figure 2c) at a V1 output of 1.0 V−0.4 ms was corrected to a narrow QRSd of 128 ms using LBBP (Figure 2d). The mean depth of the ventricular lead entry into the IVS was 9.27 ± 0.75 mm.

3.3 | Follow-up results

Septal angiography was performed in all patients to ensure that no ventricular septal perforation had occurred during the procedure (Figure 3a). The mean unipolar impedance was 662.00 ± 181.50 Ω, which was higher than 500 Ω. During the first month of follow-up, CT scans detected ventricular septal perforation in two patients, and echocardiography revealed that the ventricular lead was subendocardial in the IVS (Figure 3b1, b2, c1, c2). Penetration of the ventricular lead through the IVS to the left ventricle was confirmed using CT and echocardiography in both patients (Figure 3d1, d2). Postoperative echocardiography showed that the mean depth of the ventricular lead into the IVS in these four patients was 10.10 ± 0.858 mm. Since there was no significant change in pacing parameters before discharge, such as pacing threshold (0.875 ± 0.217 V), sensing amplitude (11.85 ± 3.04 mV), impedance (774.00 ± 89.27 Ω) or other parameters compared with those of multiple follow-ups, and these patients had no obvious discomfort, the ventricular lead position was not adjusted again. The pacing unipolar impedance exhibited a decreasing trend. These four patients received 110 mg of dabigatran orally after the discovery of the ventricular electrode perforation to prevent thrombosis and embolism. During the 24-month follow-up period, no patients experienced ventricular thrombus or stroke, as shown in Table 3. The follow-up information on these patients revealed that all patients with LBBP had a stable pacing threshold at 1 month (0.688 ± 0.25 V), 3 months (0.75 ± 0.094 V), 6 months (0.75 ± 0.58 V), 12 months.

### Table 1 Baseline characteristics of atrioventricular block patients on whom left bundle branch area pacing was performed

| Variables                              | Results          |
|----------------------------------------|------------------|
| Age, years                             | 66.04 ± 2.55     |
| Male, n (%)                            | 17 (51.5)        |
| Body mass index, kg/m²                 | 24.33 ± 0.51     |
| Cerebral infarction, n (%)             | 2 (6.06)         |
| Hyperlipidemia, n (%)                  | 9 (27.3)         |
| Hyperuricemia, n (%)                   | 2 (6.06)         |
| Hypertension, n (%)                    | 12 (36.4)        |
| Diabetes, n (%)                        | 6 (18.2)         |
| AVB                                    |                  |
| Second-degree AVB, n (%)               | 5 (15.2)         |
| Complete AVB, n (%)                    | 11 (33.3)        |
| Sinus node dysfunction combined, n (%) | 4 (12.1)         |
| Paroxysmal atrial fibrillation, n (%)  | 10 (30.3)        |
| Baseline heart diseases                |                  |
| Coronary artery disease, n (%)         | 15 (45.5)        |
| Previous MI or received PCI/CABG, n (%)| 4 (12.1)         |
| Postaortic or mitral valve replacement, n (%) | 3 (9.09) |
| Hypertrophic cardiomyopathy, n (%)     | 1 (3.03)         |
| Baseline echocardiography              |                  |
| Left ventricular end-diastolic diameter, mm | 48.48 ± 0.75   |
| Left ventricular ejection fraction, %  | 60.73 ± 1.13     |
| Ventricular septum, mm                 | 10.08 ± 0.40     |
| Baseline electrocardiogram             |                  |
| Heart rate, beats/min                  | 53.79 ± 2.29     |
| QRS duration, ms                       | 115.12 ± 4.78    |
| Left bundle branch block, n (%)        | 8 (24.2)         |
| Right bundle branch block, n (%)       | 5 (15.2)         |

Note: Total LBBAP tried: n = 33. Data were presented as mean ± standard deviation for continuous variables, and category variables were presented as number and percentages.

### Table 2 Pacing characteristics during the procedure

| Variables                              | LBBAP (N = 33) |
|----------------------------------------|----------------|
| Targeted pacing site of right ventricular septal endocardium |                  |
| Paced QRS duration, ms                 | 119.72 ± 2.53  |
| Mid notch QRS in precordial lead V1, n (%) | 31 (93.9)     |
| Anodal captured at 1 V @0.4 ms, n (%)  | 20 (60.6)      |
| LBBAP unipolar impedance, Ω            | 662.00 ± 181.5 |
| Sensing amplitude, mV                  | 14.00 ± 1.47   |

Abbreviations: LI et al., AVB, atrioventricular block; CABG, coronary artery bypass grafting; LBBAP, left bundle branch area pacing; MI, myocardial infarction; PCI, percutaneous coronary intervention.
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(0.75 ± 0.36 V), and 24 months (0.88 ± 0.50 V) without significant change (p > .05). The unipolar impedance showed a small downward trend at the 1-month follow-up (541.73 ± 13.22 Ω), but it did not change significantly at 3 months (527.50 ± 21.48 Ω), 6 months (517.71 ± 24.07 Ω), 12 months (515.68 ± 23.88 Ω) or 24 months (510.33 ± 21.39 Ω) (p > .05), as shown in Table 4.

4 | DISCUSSION

4.1 | Main findings

The 3830 electrode can be screwed into and capture the left bundle branch to obtain a narrow QRS (Li, Li, et al., 2019). LBBP has a more stable, lower pacing threshold, and better sensing amplitude than HBP (Li, Chen, et al., 2019; Vijayaraman et al., 2019). Since the distance from the anodal ring to the tip of the 3830 lead is much longer than the mean thickness of the IVS, septal perforation is a major concern for pacing in the left bundle branch region. Our study revealed that septal perforation occurred during the first month of follow-up. No dynamic changes in sensing, pacing threshold or unipolar impedance occurred during the 24-month follow-up period, and 110 mg of dabigatran twice a day was used to prevent thrombosis and embolism. Whether minor perforation increases the risk of thrombosis remains to be determined.

4.2 | Dynamic changes of LBBP

Although the left bundle branch potential cannot be recorded for all patients, we can still capture the left bundle branch and complete the LBBP using fluoroscopic imaging and changes in the V1 lead notch to obtain a narrower QRSd. Both the procedure time and fluoroscopy time decreased with increasing experience. The capture threshold, R-wave amplitude and paced QRS morphology remained stable during the follow-up period. No patient experienced a deterioration in cardiac function or increased tricuspid regurgitation according to the postoperative follow-up echocardiography. Previous studies have demonstrated that LBBP is successful, but there are no more reports on success rates or long-term pacing stability in large sequential series (Chen et al., 2018).

4.3 | How to minimize lead perforation

It is inconclusive whether ventricular septal perforation occurred. Huang proposed that unipolar impedances below 500 Ω tested during surgery are an indication of septal perforation (Huang et al., 2019). Some physicians use intracardiac ultrasound to help determine the location of the ventricular lead and determine whether ventricular septal perforation has occurred. However, this method is time-consuming and expensive and, therefore, not conducive to universal development. Before securing the ventricular lead, the operator performs an interventricular septal angiogram to determine whether any contrast has flowed into the left ventricle. If it has not, this confirms that the ventricular lead has not penetrated the left ventricle. However, many tiny ventricular septal perforations may not be identified using this method.

In our study, the unipolar impedance tested above 500 Ω in all patients during the LBBP procedure. All the patients underwent interventricular septal angiography without a contrast flow into the LV cavity. All the patients underwent echocardiography on the second day after LBBP to determine the position of the ventricular electrode and the occurrence of ventricular septal perforation. In
two patients, the ventricular electrode was found to have passed through the IVS and reached the cavity at the 1-month follow-up. A review of cardiac CT scans in two patients at the 1-month follow-up also confirmed that the ventricular electrode had penetrated the IVS into the LV cavity. Echocardiography revealed that the ventricular electrode was located under the LV septum on the second day and 1-month postoperation in two patients. A CT scan at the 1-month follow-up showed that the ventricular electrode was suspected to have penetrated the IVS into the LV cavity. Using ultrasound imaging, we found that during both systole and diastole, when the tip of the lead was against the IVS, the lead did not pass through the IVS. Although the tip of the lead does not follow systole during systole and diastole, the lead penetrates the IVS to reach the LV cavity. 

These four patients were followed up after 1, 3, 6, 12 and 24 months, and there was no significant change in pacing parameters, such as pacing threshold, R-wave, and impedance (p > .05), which may be because the anode ring of the ventricular electrode was still in the IVS and the myocardial contact was good. During the postoperative follow-up of the patients with ventricular lead perforation, it was found that the pacing unipolar impedance exhibited a downward trend, which may be related to the electrode tip penetrating the IVS.

Two patients were discharged from the hospital after echocardiography, which revealed ventricular electrode perforation. However, follow-up at 1-month postsurgery revealed ventricular lead perforation, which may have been caused by ventricular contraction and interventricular septal compression. Perforation of ventricular leads can cause local thrombosis. Therefore, patients with ventricular septal perforation were treated with 110 mg of dabigatran twice a day for the prevention of thrombosis and embolism. Current follow-up has not revealed any cases of ventricular thrombosis, new cerebral infarction or pulmonary embolism.

Through the follow-up of these four patients, we found that if the lead penetrated the IVS by 1 mm, ventricular lead perforation could be identified through echocardiography and cardiac CT. If the ventricular lead was very close to the LV surface of the IVS, the location of the ventricular lead tip in the cardiac CT scan was greatly interfered with by the artifacts. It is not easy to determine whether the ventricular lead has caused perforation from a CT scan.

In summary, our study found that in addition to performing an interventricular septal angiogram intraoperatively to determine whether contrast had flowed into the LV cavity and noting the unipolar impedance of the ventricular lead, regular follow-up imaging was necessary to determine the position of the ventricular lead tip. Some ventricular lead perforations may occur 1 month after the LBBP procedure. For patients who experience ventricular lead perforation after LBBP, anticoagulation should be administered orally to prevent thrombosis and embolism.

4.4 Limitations

Our study was a single-center study with a small sample size and a follow-up time of up to 24 months. We should expand the sample size and prolong the follow-up time to better judge the safety and efficacy of pacing in the left bundle branch region. Patients with ventricular lead perforation require longer follow-up to observe changes in the pacing parameters and the incidence of thrombosis and embolism. Measurement error may be inevitable for echocardiographic parameters. Echocardiographic acquisition can be affected by noisy signals. The parameters we used to describe telex, although readily available, are not accurate.
TABLE 3 Complications and changes in pacing parameters within 24 months after left bundle branch area pacing

|                        | LBBAP (n = 33) |
|------------------------|---------------|
|                        | Before discharge | 1-month follow-up | 3-month follow-up | 6-month follow-up | 12-month follow-up | 24-month follow-up |
| Pacing parameters      |               |                 |                 |                 |                 |                 |
| Sensing amplitude, mV  | 14.00 ± 1.47  | 19.50 ± 5.30    | 17.01 ± 1.30    | 17.32 ± 3.24    | 16.88 ± 2.48    | 15.02 ± 3.57    |
| p Value                |               |                 |                 |                 |                 |                 |
| Pacing threshold @0.4 ms, V | 0.75 ± 0.50  | 0.688 ± 0.25    | 0.75 ± 0.094    | 0.75 ± 0.58    | 0.75 ± 0.36    | 0.88 ± 0.50    |
| p Value                |               |                 |                 |                 |                 |                 |
| Unipolar pacing impedance, Ω | 662.00 ± 181.50 | 541.73 ± 13.22 | 527.50 ± 21.48 | 517.71 ± 24.07 | 515.68 ± 23.88 | 510.33 ± 21.39 |
| p Value                |               |                 |                 |                 |                 |                 |
| Complication, n (%)    | 0 (0)         | 2 (6.06)        |                 |                 |                 |                 |
| Infection, n (5)       | 0 (0)         | 0 (0)           | 0 (0)           | 0 (0)           | 0 (0)           | 0 (0)           |
| Septal perforation, n (%) | 0 (0)         | 2 (6.06)        | 0 (0)           | 0 (0)           | 0 (0)           | 0 (0)           |
| Lead dislodgment, n (%) | 0 (0)         | 0 (0)           | 0 (0)           | 0 (0)           | 0 (0)           | 0 (0)           |

Abbreviation: LBBAP, left bundle branch area pacing.

TABLE 4 The pacing parameters within 24 months after LBBAP in the ventricular lead perforation patients

|                        | Before discharge | 1-month follow-up | 3-month follow-up | 6-month follow-up | 12-month follow-up | 24-month follow-up |
|------------------------|------------------|-------------------|-------------------|-------------------|-------------------|-------------------|
| Septal thickness, mm   | 10.00 ± 0.408    |                   |                   |                   |                   |                   |
| Ventricular lead depth, mm | 10.10 ± 0.858  |                   |                   |                   |                   |                   |
| Pacing parameters      |                  |                   |                   |                   |                   |                   |
| Sensing amplitude, mV  | 11.85 ± 3.04     | 9.03 ± 2.17       | 9.90 ± 2.91       | 10.3 ± 2.62       | 9.67 ± 2.38       | 9.32 ± 2.23       |
| P Value                | .546             | .686              | .754              | .675              | .598              |                   |
| Unipolar pacing impedance, Ω | 744.00 ± 89.27 | 554.00 ± 49.00   | 524.00 ± 42.93   | 517.50 ± 42.30   | 512.00 ± 42.20   | 510.40 ± 21.90   |
| p Value                | .073             | .054              | .048              | .044              | .042              |                   |

5 | CONCLUSIONS

The LBBP zone is safe and effective in patients with AVB. Using the technique described in this paper, we can safely and successfully perform LBBP in 100% of patients. LBBP can correct both a right and LBBB. Patients with LBBP have a narrowed QRS complex and more physiologic pacing. LBBP intraoperative ventricular septal angiography and unipolar impedance can help determine whether ventricular septal perforation occurs. Postoperative follow-up is necessary to help detect delayed ventricular lead perforation. For patients with ventricular electrode perforation, oral anticoagulant therapy should be given to prevent thrombosis and embolism.

AUTHOR CONTRIBUTIONS
Conception and design of the research: LQY, GCJ. Acquisition of data: LQY, DWL, FDP. Analysis and interpretation of the data: LQY, MWL, LCC. Statistical analysis: LQY, GCJ, LCS, HDF, LX. Obtaining financing: None. Writing of the manuscript: LQY, DWL. Critical revision of the manuscript for intellectual content: GCJ.
All of the authors had no any personal, financial, commercial, or academic conflicts of interest separately.

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

This study was conducted in accordance with the Declaration of Helsinki and approved by the ethics committee of Beijing Anzhen Hospital, and informed consent was obtained from the participant.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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