계명의대학술지
Keimyung Medical Journal

Original Article

pISSN 2092-8335 · eISSN 2733-5380
Keimyung Med J 2025;44(1):39-49
https://doi.org/10.46308/kmj.2025.00052

Received: April 8, 2025
Revised: April 20, 2025
Accepted: April 28, 2025

Corresponding Author:
Jongmin Hwang, MD, PhD, CCDS, CEPS-A
Division of Cardiology, Department of Internal Medicine, Keimyung University Dongsan Hospital, Keimyung University College of Medicine, 1035 Dalgubeol-daero, Dalseo-gu, Daegu 42601, Korea
E-mail: dsmcep@gmail.com

Comparative Analysis of Different Manufacturer Products for Left Bundle Branch Area Pacing: a Real-world Single Center Experience

Min-Su Jung, Jongmin Hwang, Tae-Wan Chung, Hyoung-Seob Park

Division of Cardiology, Department of Internal Medicine, Keimyung University Dongsan Hospital, Keimyung University School of Medicine, Daegu, Korea

Left bundle branch area pacing (LBBAP) has emerged as a promising physiological pacing alternative. However, limited data exist comparing different manufacturer systems for this technique. This prospective single-center study evaluated the real-world performance of four manufacturer systems during our learning phase with LBBAP. We included 214 consecutive patients who underwent LBBAP between July 2021 and March 2025 using Biotronik (n = 44), Abbott (n = 35), Boston Scientific (n = 46), and Medtronic (n = 88) systems. The overall success rate was 83.2%, with significant differences among manufacturers (Medtronic, 93.2%; Boston Scientific, 78.3%; Abbott, 77.1%; and Biotronik, 72.7%; $p < 0.001$). Success rates improved over time, from 0% in the initial cases to consistently above 80% from mid-2024 onward, demonstrating a clear learning curve. The Medtronic lumenless lead system showed superior performance despite its inability to perform continuous unipolar electrogram monitoring during lead advancement. Advanced age did not negatively impact success rates, with similar outcomes between patients aged < 70 years (81.5%) and ≥ 70 years (84.8%, $p = 0.11$). The overall complication rate was 6.5%, with septal perforation (3.3%) and lead dislodgement (2.3%) being the most common complications. Each manufacturer system presented distinct advantages and limitations: the Medtronic system offered higher success rates but more lead dislodgements (4.5%), whereas stylet-driven leads provided better electrogram monitoring but lower success rates. Our findings suggest that the Medtronic lumenless lead system is preferred for centers implementing LBBAP, particularly during the learning phase, while highlighting the importance of understanding the unique technical characteristics of each system.

Keywords: Left bundle branch area pacing, Lumen less lead, Stylet-driven lead, Lead delivery system, Learning curve

Introduction

Left bundle branch area pacing (LBBAP) is a promising physiological pacing method that offers more synchronous ventricular activation than conventional right ventricular (RV) pacing [1]. Since its first description by Huang et al. [2] in 2017, LBBAP has evolved from an experimental technique to an increasingly adopted approach in patients requiring ventricular pacing. The fundamental principle of LBBAP involves positioning a pacing lead deep within the interventricular septum to capture the left bundle branch (LBB) or its fascicular network. This pacing strategy theoretically provides more natural left ventricular (LV) activation patterns and improves hemodynamics compared with traditional RV apical or septal pacing [3]. Additionally, LBBAP has demonstrated advantages over His bundle pacing (HBP) in terms of higher success rates, low-

er capture thresholds, and the ability to overcome distal conduction system disease [4].

Despite its increasing popularity, LBBAP faces challenges related to the standardization of implantation techniques and equipment [5]. This procedure requires specialized tools, including specifically designed delivery sheaths and pacing leads capable of penetrating the interventricular septum to reach the target area. Various manufacturers have developed different lead delivery systems for LBBAP, each with unique design characteristics that may influence procedural success and long-term performance [6-9].

In South Korea, the adoption of LBBAP has followed a regulated timeline of product approval by the Ministry of Food and Drug Safety. In July 2021, our center began implementing LBBAP procedures using products from various manufacturers in the sequential order of their regulatory approval. This provided a unique opportunity to evaluate the real-world performances of different systems during the learning phase.

The available lead systems for LBBAP can be broadly categorized into two types: lumenless leads (LLLs) and stylet-driven leads (SDLs) [10]. The Medtronic SelectSecure 3830 lead, a 4.1 Fr LLL with a fixed helix, was the first lead used for conduction system pacing. Subsequently, conventional SDLs with extendable-retractable helices from manufacturers, including Biotronik, Abbott, and Boston Scientific, have been adopted for LBBAP. Each lead type has distinct mechanical properties, handling characteristics, and delivery methods that may influence implantation success and complications [11].

In this context, our study aimed to evaluate the real-world efficacy and procedural safety of different manufacturer products for LBBAP during our center's learning phase with this technique. By analyzing success rates, procedural characteristics, and complications across different lead-sheath combinations, we sought to provide insights that may guide product selection, improve procedural outcomes, and potentially inform future technological developments in this rapidly evolving field.

Methods

Study design and patient population

This single-center prospective observational study was conducted at Keimyung University Dongsan Hospital, Daegu, South Korea. We prospectively enrolled consecutive patients who underwent LBBAP between July 2021 and March 2025. Patients had either standard bradycardia indications for permanent pacemaker implantation (including sinus node dysfunction and atrioventricular block) or cardiac resynchronization therapy (CRT) indications according to the current guidelines.

For patients with bradycardia indications, LBBAP was selected as the preferred pacing modality to avoid the potential adverse effects of RV pacing, such as pacing-induced cardiomyopathy and heart failure [12]. For CRT candidates, we selectively performed LBBAP in three patients with nonischemic cardiomyopathy who had minimal structural remodeling and true left bundle branch block (LBBB) morphology, suggesting a proximal left conduction system block [13,14]. These characteristics made them suitable candidates for direct LBB capture rather than conventional biventricular pacing.

The study protocol was approved by the Institutional Review Board of Keimyung University Dongsan Hospital (approval number: 2021-08-092). All patients provided written informed consent for the procedure and participation in the study, which was conducted in accordance with the Declaration of Helsinki and the Good Clinical Practice guidelines.

All procedures were performed by the same operator who was experienced in cardiac device implantation but in the initial learning phase of LBBAP techniques. This consistent operator approach allowed for a more reliable assessment of the learning curve and performance differences between the lead systems without the confounding effect of multiple operators with varying experience levels.

Left bundle branch area pacing procedure

All LBBAP procedures were performed in the cardiac electrophysiology laboratory under local anesthesia with conscious sedation as needed. Following standard surgical preparation, vascular access was obtained via a left or right subclavian or axillary vein puncture using a modified Seldinger technique. A standard 12-lead electrocardiogram was recorded continuously during the procedure, and unipolar electrograms from the lead tip were monitored to identify conduction system capture.

The detailed methodology for LBBAP and techniques for confirming conduction system capture have been previously described in our earlier publications and were consistently applied across all manufacturer systems in this study [15]. Briefly, the general approach for LBBAP consisted of the following steps: After gaining vascular access, a guidewire was advanced into the RV under fluoroscopic guidance. An appropriate delivery sheath for each lead system was introduced over the guidewire and positioned in the RV. The sheath was oriented to face the mid-to-lower interventricular septum,

approximately 1–2 cm distal to the His bundle recording site, targeting the LBB area. Once in position, the pacing lead was advanced through the sheath to contact the interventricular septum.

For septal penetration, we employed clockwise rotation of the lead while maintaining gentle forward pressure against the septum. Successful penetration was confirmed using the following:

1. Characteristic changes on the unipolar lead electrogram showing ST-segment elevation (injury current)
2. Gradual changes in paced QRS morphology from a LBBB pattern to a narrow QRS or right bundle branch block pattern
3. Fluoroscopic confirmation of lead advancement into the septum

Lead delivery systems and manufacturer-specific techniques

We used five different lead delivery sheath combinations from four manufacturers, each of which received approval from the Ministry of Food and Drug Safety of South Korea. The chronological adoption of these systems was as follows:

1) Biotronik system (July 2021 to present): Selectra sheath with Solia lead

The Biotronik Selectra delivery sheath (55-42, or 65-42 according to patient anatomy, Biotronik Selectra 3D; Biotronik SE & Co. KG, Berlin, Germany) was used to deliver the Solia S pacing lead (5.6 Fr active fixation lead with extendable-retractable electrically active helix, Biotronik Solia S60; Biotronik SE & Co. KG, Berlin, Germany). The procedure was initiated by advancing the delivery sheath into the RV septum. Prior to septal penetration, the helix was fully extended, and the stylet was advanced to the lead tip for maximal support. The sheath was positioned perpendicular to the target site to achieve optimal force transmission.

For septal deployment, clockwise rotation was applied to the proximal lead body while maintaining gentle forward pressure. To prevent unwanted helix retraction during rotations, we employed a locking technique using a stylet insertion tool [16]. Continuous unipolar pacing through the stylet allowed real-time monitoring of electrogram changes and paced QRS morphology during penetration (Supplementary Video 1).

2) Abbott His Pro with Tendril™ 2088TC lead (March 2023 to present)

The Abbott HisPro™ Steerable sheath (Agilis HisPro™; Abbott Inc, Abbott Park, IL, USA) featured a deflectable design that facilitated precise positioning against the interventricular septum. After navigating the sheath to the target area, the deflectable mechanism was used to achieve perpendicular orientation to the septum. The 5.8Fr Tendril™ 2088TC active fixation lead (Tendril™ STS pacing lead; Abbott Inc, Abbott Park, IL, USA) was prepared by fully extending the helix and advancing the stylet to the lead tip.

The lead was then advanced through the sheath, with gentle but firm pressure applied during clockwise rotation to facilitate septal penetration. The steerable nature of the sheath allowed fine adjustments to optimize the lead-tissue interface angle. During lead advancement, we carefully monitored for evidence of helix retraction, a known limitation of SDLs, and reextended the helix when necessary (Supplementary Video 2).

3) Boston Scientific SSPC with Ingevity+ lead (July 2023 to present)

The Boston Scientific SSPC delivery sheaths (SSPC3; Boston Scientific Corporation, Marlborough, Massachusetts, USA) were used with the 6 Fr Ingevity+ active fixation lead (INGEVITY+; Boston Scientific Corporation, Marlborough, Massachusetts, USA). After the sheath was positioned to achieve perpendicular orientation to the septum, the Ingevity+ lead prepared with a fully extended helix was advanced through the sheath.

Septal penetration was achieved through clockwise rotation with controlled forward pressure. Particular attention was paid to the lead-sheath alignment, as improper alignment could lead to lead tip bending and potential helix damage. If resistance was encountered during penetration, the sheath orientation was reassessed rather than increasing the rotational force to avoid lead damage (Supplementary Video 3).

4) Medtronic C315 sheath with 3830 SelectSecure lead (March 2024 to present)

The Medtronic C315His delivery sheath (C315His; Medtronic Inc, Minneapolis, MN) was positioned against the interventricular septum of the target region. The 4.1 Fr lumenless 3830 SelectSecure lead (SelectSecure 3830; Medtronic Inc, Minneapolis, MN) with a fixed helix was advanced through the sheath until contact with the septum was achieved. Given the fixed helix design, no pre-deployment preparation of the lead was required.

Septal penetration was accomplished exclusively through the clockwise rotation of the lead body. The absence of a re-

tractable helix mechanism eliminated concerns regarding helix retraction during deployment. While the lead was more flexible than stylet-driven alternatives, proper orientation of the C315His sheath provided adequate support for septal penetration. However, a significant limitation of this system was its inability to perform continuous unipolar electrogram monitoring during lead advancement, making it more challenging to confirm successful septal penetration and conduction system capture. Instead, we relied primarily on fluoroscopic guidance and intermittent pacing checks to verify the lead position and conduction system capture (Supplementary Video 4).

5) Abbott CPS Locator with Tendril 2088TC lead (June 2024 to present)

The Abbott CPS Locator 3D catheter (medium or large, according to the patient's anatomy, CPS Locator 3D; Abbott Inc, Abbott Park, IL, USA) was the most recently introduced system in our practice. This non-deflectable sheath was positioned to achieve optimal perpendicular orientation to the septum before lead advancement. The same Tendril 2088TC lead (Tendril™ STS pacing lead; Abbott Inc, Abbott Park, IL, USA) used in the His Pro system was used with the sheath.

The design of the CPS Locator facilitated stable positioning against the septum, allowing controlled force application during lead rotation. Similar to other SDLs, the helix was fully extended prior to deployment, and clockwise rotation was applied to achieve septal penetration. We utilized a dedicated helix locking tool with this system to prevent unwanted helix retraction during the rotation and penetration processes. This technical addition provided greater stability during lead advancement and enhanced the precision of septal penetration (Supplementary Video 5).

6) Final lead position confirmation and procedure completion

For all systems, once satisfactory lead position was achieved with appropriate electrical parameters (pacing threshold < 2.0 V at 0.4 ms, R-wave sensing > 5.0 mV, and impedance within normal range), the delivery sheath was carefully withdrawn using standard slitting technique while maintaining lead position. The lead was connected to an appropriate generator, and the pocket was closed using standard techniques.

Statistical analysis

Continuous variables were expressed as mean ± standard deviation and compared using Student's t-test or one-way analysis of variance (ANOVA) with post hoc Bonferroni correction for multiple comparisons. Categorical variables are presented as numbers and percentages and compared using the chi-square test or Fisher's exact test, as appropriate.

Success rates between manufacturer systems were compared using the chi-square test, and 95% confidence intervals were calculated using the Wilson score method. To evaluate the learning curve effect, we compared the success rates between early cases (first 10 procedures) and subsequent cases for each manufacturer system using Fisher's exact test.

Procedural parameters (procedure and fluoroscopy times) were compared across manufacturer systems using one-way ANOVA, followed by Bonferroni post hoc analysis. To assess the independent predictors of LBBAP success, we performed multivariate logistic regression analysis, including patient characteristics (age and sex), procedure type, and manufacturer system as covariates.

Statistical significance was defined as a two-sided p-value < 0.05.

Results

Patient characteristics

Between July 2021 and March 2025, 214 consecutive patients underwent LBBAP at our center. The cohort included 122 females (57.0%) and 92 males (43.0%), with a mean age of 70.9 ± 10.5 years. Most procedures (98.1%, 210/214) were performed for permanent pacemaker indications, whereas 4 patients (1.9%) underwent CRT with LBBAP. Of these patients, three had true LBBB morphology [13,17], and one underwent CRT after atrioventricular node ablation for persistent atrial fibrillation.

Table 1 presents the baseline demographic and clinical characteristics of the patients stratified by manufacturer. Notably, patients who received Biotronik devices were significantly younger (mean age 63.9 ± 11.7 years) than those who received other manufacturer systems (Abbott: 72.3 ± 9.6 years, Boston Scientific: 74.5 ± 7.6 years, Medtronic: 72.0 ± 9.8 years; p < 0.001). This age difference may be due to our cautious approach during the initial implementation phase of LBBAP, when we preferentially selected younger patients with potentially fewer comorbidities to minimize procedural complications while gaining experience with this novel technique. No significant differences were observed in sex distribution or procedure indications across the manufacturer groups.

Procedural success rates

The overall success rate of LBBAP was 83.2% (178/214). As

Table 1. Baseline patient characteristics

Characteristic	Overall (n = 214)	Biotronik (n = 44)	Abbott (n = 35)	Boston Scientific (n = 46)	Medtronic (n = 88)	*p*-value
Demographics						
Age, yr	70.9 ± 10.5	63.9 ± 11.7	72.3 ± 9.6	74.5 ± 7.6	72.0 ± 9.8	< 0.001
Female	122 (57.0)	22 (50.0)	18 (51.4)	29 (63.0)	52 (59.1)	0.420
Pacing indication						
Sinus node dysfunction	69 (32.2)	14 (31.8)	11 (31.4)	15 (32.6)	29 (33.0)	0.990
AV block and others	145 (67.8)	30 (68.2)	24 (68.6)	31 (67.4)	59 (67.0)	-
Comorbidities						
Diabetes mellitus	40 (26.7)	10 (23.8)	7 (26.9)	11 (27.5)	12 (28.6)	0.960
Hypertension	98 (65.3)	24 (57.1)	19 (73.1)	31 (77.5)	24 (57.1)	0.047
Coronary artery disease	23 (15.3)	4 (9.5)	3 (11.5)	8 (20.0)	8 (19.0)	0.390
Heart failure	15 (10.0)	3 (7.1)	1 (3.8)	7 (17.5)	4 (9.5)	0.260
Severe valvular disease	11 (7.3)	3 (7.0)	1 (3.8)	3 (7.5)	4 (9.5)	0.830
Atrial fibrillation	45 (29.8)	4 (9.3)	5 (19.2)	14 (35.0)	22 (52.4)	< 0.001
Procedure type						0.510
Pacemaker	210 (98.1)	42 (95.5)	35 (100.0)	46 (100.0)	86 (97.7)	
CRT	4 (1.9)	2 (4.5)	0 (0.0)	0 (0.0)	2 (2.3)	
Echocardiographic parameters						
LVDd, mm	5.0 ± 0.5	5.0 ± 0.5	4.9 ± 0.5	5.1 ± 0.4	5.0 ± 0.6	0.730
LVDs, mm	3.3 ± 0.6	3.3 ± 0.6	3.2 ± 0.4	3.6 ± 0.5	3.3 ± 0.7	0.160
LVEF, %	58.4 ± 11.0	60.1 ± 10.8	57.1 ± 10.1	55.5 ± 11.6	58.8 ± 11.3	0.520
LAD, mm	4.4 ± 0.7	4.4 ± 0.8	4.4 ± 0.6	4.5 ± 0.7	4.4 ± 0.7	0.890

Values are presented as mean ± standard deviation or n (%).
AV, atrioventricular; CRT, cardiac resynchronization therapy; LVDd, left ventricular diastolic diameter; LVDs, left ventricular systolic diameter; LVEF, left ventricular ejection fraction; LAD, left atrial diameter.

shown in Fig. 1, success rates varied significantly across manufacturer systems. Medtronic had the highest success rate (93.2%, 82/88), followed by Boston Scientific (78.3%, 36/46), Abbott (77.1%, 27/35), and Biotronik (72.7%, 32/44). The difference in success rates between the Medtronic system and the other manufacturers was statistically significant ($p < 0.001$), whereas the differences among the SDL systems did not reach statistical significance ($p = 0.810$).

Chronological analysis and learning curve

Fig. 2 illustrates the success rates by calendar quarter from Q3 2021 to Q1 2025, reflecting our center's learning curve with LBBAP. The success rates showed a clear improvement trend over time, starting from 0% in the initial cases (Q3 2021) and rising to consistently above 80% from Q2 2024 onward. The most notable improvements occurred between Q2 2022 (66.7%) and Q3 2022 (90.9%), suggesting a relatively rapid learning curve for the procedure.

Table 2 presents the impact of the learning curve on each manufacturer system, comparing the success rates between early cases (first 10 procedures) and subsequent cases. The Biotronik and Boston Scientific systems showed the most pronounced learning curve effects, with success rates improving from 50.0% to 79.4% and 60.0% to 83.3%, respectively. The Medtronic system demonstrated high success rates from the beginning (90.0% in early cases and 93.6% in later cases), suggesting that it is less operator-dependent. The Abbott system showed a reverse trend, with a slight decrease in success rates from early to later cases (90.0% to 72.0%), potentially indicating technical challenges that persisted beyond the initial experience.

Subgroup analysis

Subgroup analyses were performed to identify patient-related factors that might influence procedural success (Table 3).

Considering that the mean age of our cohort was 70.9 years, we analyzed the success rates using 70 years as the cutoff point. As shown in Table 3, success rates were similar between patients younger than 70 years (81.5%) and those 70 years or older (84.8%, $p = 0.11$), indicating that advanced age was not a limiting factor for LBBAP success. The high success rate observed in older patients suggests that LBBAP can be safely

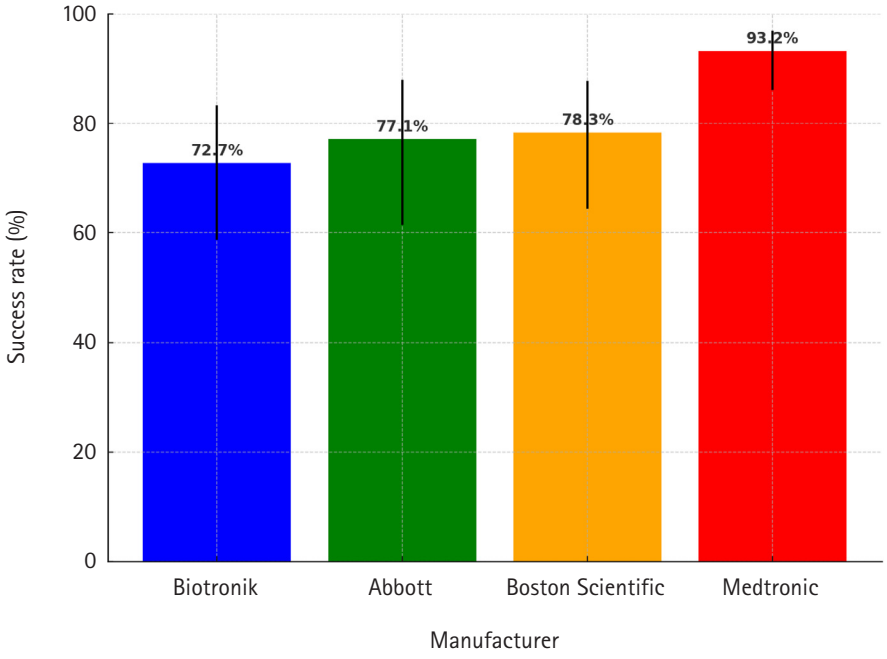

Fig. 1. Success rates of left bundle branch area pacing with different manufacturer systems. Success rates were significantly higher with the Medtronic lumenless lead system (93.2%) than with the stylet-driven lead systems from Biotronik (72.7%), Abbott (77.1%), and Boston Scientific (78.3%; $p < 0.001$). Error bars represent 95% confidence intervals.

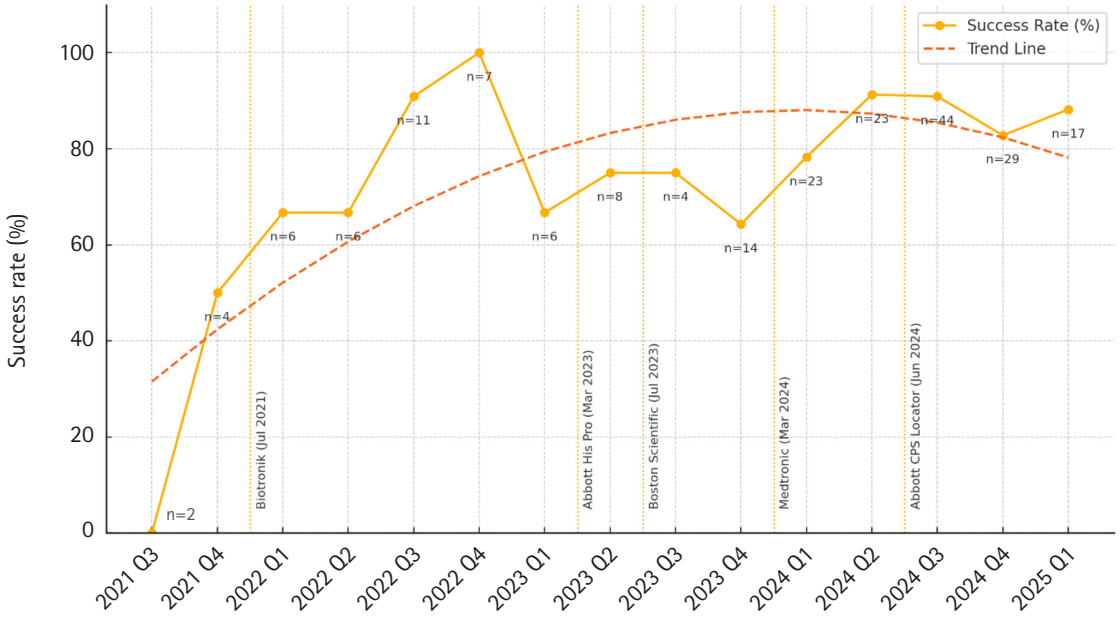

Fig. 2. Success rates by quarter (2021–2025). Chronological trend of success rates of left bundle branch area pacing by quarter from July 2021 to March 2025. Vertical dotted lines indicate the introduction of different manufacturer systems. The graph demonstrates an overall improvement in success rates over time, reflecting the learning curve effect. Note the initial improvement phase in 2022, followed by some fluctuation in 2023, and then consistently high success rates (> 80%) from Q2 2024 onward, coinciding with the adoption of the Medtronic system.

performed regardless of age and may be considered a more physiological pacing option, even for older patients who would otherwise undergo conventional RV pacing.

Female patients showed a trend toward higher success rates than male patients (86.1% vs. 78.3%, $p = 0.13$). Among those with comorbidities, patients with heart failure had somewhat lower success rates (66.7% vs. 81.5% in those without heart failure, $p = 0.18$); however, no other comorbidity significantly impacted procedural success. The LV ejection fraction did not significantly affect success rates.

These findings suggest that LBBAP can be performed effectively across diverse patient populations with various comorbidities; however, larger studies are needed to confirm these trends.

Procedural parameters

The fluoroscopy time and total procedure duration were available for 178 successful LBBAP procedures. Table 4 presents the parameters stratified by manufacturer. Successful procedures performed using the Medtronic system had significantly shorter procedure times (76 ± 18 minutes vs. 89 ± 24 minutes for other systems, $p < 0.001$) and fluoroscopy times (10.3 ± 4.2 minutes vs. 14.2 ± 6.8 minutes for other systems, $p < 0.001$), indicating greater procedural efficiency with the LLL system.

Acute complications

The overall acute complication rate was 6.5% (14/214), with no significant differences observed across the manufacturer systems (Table 5). The most common complications were septal perforation (3.3%, 7/214) and lead dislodgement (2.3%, 5/214), followed by pneumothorax (0.5%, 1/214) and septal hematoma (0.5%, 1/214). No procedure-related deaths occurred.

The complication profile demonstrated that LBBAP can be performed with reasonable safety across all manufacturer systems. Lead dislodgement was more common with the Medtron-

Table 2. Impact of learning curve on success rates by manufacturer

Manufacturer	Early cases (first 10)	Later cases	*p*-value
Biotronik	50.0 (5/10)	79.4 (27/34)	0.07
Abbott	90.0 (9/10)	72.0 (18/25)	0.25
Boston Scientific	60.0 (6/10)	83.3 (30/36)	0.11
Medtronic	90.0 (9/10)	93.6 (73/78)	0.68

Values are presented as % (n).

Table 3. Success rates by subgroups

Subgroup	Success rate	*p*-value
Age group (yr)		0.11
< 70	81.5 (88/108)	
≥ 70	84.8 (90/106)	
Sex		0.13
Male	78.3 (72/92)	
Female	86.1 (105/122)	
Comorbidities		
Diabetes mellitus		0.99
Yes	80.0 (32/40)	
No	80.0 (88/110)	
Hypertension		0.80
Yes	80.6 (79/98)	
No	78.8 (41/52)	
Coronary artery disease		0.43
Yes	73.9 (17/23)	
No	81.1 (103/127)	
Heart failure		0.18
Yes	66.7 (10/15)	
No	81.5 (110/135)	
Severe valvular disease		0.89
Yes	81.8 (9/11)	
No	80.0 (112/140)	
Atrial fibrillation		0.63
Yes	77.8 (35/45)	
No	81.1 (86/106)	
Left ventricular function		0.72
LVEF < 40%	80.0 (4/5)	
LVEF 40%–50%	75.0 (6/8)	
LVEF > 50%	84.4 (38/45)	
Procedure type		0.35
Pacemaker	82.4 (173/210)	
CRT	100.0 (4/4)	

Values are presented as % (n).
LVEF, left ventricular ejection fraction; CRT, cardiac resynchronization therapy.

Table 4. Procedural parameters for successful left bundle branch area pacing by manufacturer

Parameter	Biotronik (n = 44)	Abbott (n = 35)	Boston Scientific (n = 46)	Medtronic (n = 88)	*p*-value
Procedure time (min)	93 ± 26	91 ± 23	84 ± 21	76 ± 18	< 0.001
Fluoroscopy time (min)	16.2 ± 7.9	14.5 ± 6.3	12.4 ± 5.6	10.3 ± 4.2	< 0.001

Values are presented as mean ± standard deviation.

Table 5. Acute complications by manufacturer

Complication	Biotronik (n = 44)	Abbott (n = 35)	Boston Scientific (n = 46)	Medtronic (n = 88)	Total (n = 214)	*p*-value
Total	4 (9.1)	1 (2.9)	3 (6.5)	6 (6.8)	14 (6.5)	0.68
Septal perforation	2 (4.5)	1 (2.9)	2 (4.3)	2 (2.3)	7 (3.3)	0.83
Lead dislodgement	1 (2.3)	0 (0.0)	0 (0.0)	4 (4.5)	5 (2.3)	0.26
Septal hematoma	0 (0.0)	0 (0.0)	1 (2.2)	0 (0.0)	1 (0.5)	0.31
Pneumothorax	1 (2.3)	0 (0.0)	0 (0.0)	0 (0.0)	1 (0.5)	0.24

Values are presented as n (%).

ic system (4.5%), although the difference was not statistically significant ($p = 0.26$). Septal perforation occurred in all systems, with slightly higher rates in the Biotronik (4.5%) and Boston Scientific (4.3%) groups than in the Medtronic group (2.3%). One case of pneumothorax was observed in the Biotronik group (2.3%), and one case of septal hematoma occurred in the Boston Scientific group (2.2%).

Discussion

Comparative success rates between lead types: challenging the conventional wisdom

Our study provides several notable findings that contribute to the ongoing discussion on optimal lead systems for LBBAP. While most published literature suggests minimal differences in success rates between LLLs and SDLs, our real-world experience provides a more nuanced picture. SDLs have shown success rates of approximately 80%; however, after introducing LLLs into our practice, we experienced a dramatic improvement in procedural success, with failures becoming rare.

This performance disparity merits careful consideration. One might initially attribute this difference to our center's learning curve, particularly given our limited prior experience with LLLs for HBP and LBBAP. However, this explanation alone seems insufficient to account for the dramatic improvement in the success rates observed with LLLs. This abrupt increase in procedural success suggests that intrinsic differences in lead design and mechanical properties likely play a significant role.

Recent mechanical studies by Chapman et al. [11] have provided insights into these observations. Their ex vivo research demonstrated significant differences in torque transfer properties between lead types, with the Medtronic 3830 lead showing the lowest rate of uncontrolled torque breakpoint events despite having a lower rotation ratio. This mechanical behavior may translate into more predictable lead-handling characteristics during septal penetration, potentially explaining the improved success rates of this system.

Notably, our patient population demonstrated minimal heterogeneity in terms of the cardiac substrate, with all patients exhibiting a preserved ejection fraction and no structural heart disease. This relative homogeneity in the substrate further strengthens the fact that the observed differences in success rates are primarily attributable to the lead systems themselves rather than to patient-specific factors.

Success rates and technical considerations

The overall success rate of 83.2% in our study was comparable to the rates reported in previous LBBAP studies, which ranged from 80% to 92% [18]. However, a notable finding was the significantly higher success rate achieved with the Medtronic SelectSecure 3830 LLL system (93.2%) than with SDLs from Boston Scientific (78.3%), Abbott (77.1%), and Biotronik (72.7%). This difference can be attributed to several technical factors inherent in design and delivery systems.

The smaller diameter of the Medtronic 3830 lead (4.1 Fr vs. 5.6-6 Fr for SDLs) may facilitate easier septal penetration with less tissue trauma. In addition, its fixed-helix design eliminates the risk of helix retraction during deployment, which is a common challenge for extendable-retractable helix leads. This advantage was particularly evident in our study as we observed multiple instances of helix retraction during deployment attempts with SDLs, necessitating lead repositioning or replacement.

However, the Medtronic system has certain limitations. A significant drawback of the C315His sheath with the 3830 lead is the inability to perform continuous unipolar electrogram monitoring during lead advancement, which makes it more challenging to confirm successful septal penetration and capture of the conduction system. This limitation results in greater reliance on fluoroscopic guidance and intermittent pacing checks, potentially increasing the radiation exposure for patients and operators. Despite this limitation, the high success rate achieved with this system suggests that the benefits of the LLL design outweigh the disadvantages.

Learning curve effect

Our chronological analysis demonstrated a clear learning curve effect in LBBAP procedures, with success rates improving from 0% in our initial cases to > 80% in mid-2024. This learning curve is consistent with previous reports suggesting that 20–30 cases are typically required to achieve proficiency in LBBAP [18].

The learning curve varied among the manufacturer systems. The Biotronik and Boston Scientific systems showed substantial improvements in success rates between early and later cases (50.0% to 79.4% and 60.0% to 83.3%, respectively), indicating a steeper learning curve. In contrast, the Medtronic system demonstrated high success rates from the beginning (90.0% in early cases), suggesting that it is less operator-dependent and more suitable for centers in the early phase of LBBAP adoption.

Additionally, the learning curve varies significantly among manufacturers, further complicating the landscape. Previous studies have suggested that implantation success rates, fluoroscopy times, and procedural duration significantly improve with experience. However, this learning curve may differ between lead types and delivery systems, as highlighted by Cano et al. [10], who found that even operators with extensive experience using one lead type may require a specific learning curve for another lead type.

Patient factors and subgroup analysis

Another important finding from our subgroup analysis was that advanced age did not negatively affect LBBAP success rates. Patients aged 70 years or older had a slightly higher success rate (84.8%) than younger patients (81.5%), although this difference was not statistically significant. This finding is particularly relevant in clinical practice, as older patients comprise a significant proportion of those requiring permanent pacing and are often more susceptible to the adverse effects of RV pacing.

The slightly higher success rate observed in female patients (86.1% vs. 78.3% in males, $p = 0.13$) is a finding that warrants further investigation. This trend may be related to sex-specific differences in the cardiac anatomy, interventricular septal thickness, or myocardial properties. Previous studies on HBP reported similar sex-based differences in success rates; however, data specific to LBBAP are limited [19].

Acute complications

The overall complication rate of 6.5% in our study was within the range reported in previous LBBAP studies (3%–8%) [18]. Septal perforation was the most common complication (3.3%), followed by lead dislodgement (2.3%). Notably, lead dislodgement was more frequent with the Medtronic system (4.5%) than with the other manufacturers, although this difference was not statistically significant. This higher dislodgement rate might be related to the smaller screw size of the 3830 lead or the greater flexibility of the LLL design, potentially resulting in a less stable fixation in some cases.

Septal perforation rates were slightly higher with the Biotronik (4.5%) and Boston Scientific (4.3%) systems, possibly reflecting the larger diameter and greater stiffness of these leads, which may have increased the risk of septal trauma during deployment. A single case of septal hematoma observed using the Boston Scientific system may also be related to these factors. The pneumothorax case observed with the Biotronik system is likely related to venous access rather than to the specific lead or delivery system used.

Despite these complications, no procedure-related deaths or serious adverse events requiring surgical intervention occurred, confirming the overall safety of LBBAP across different manufacturer systems.

Implications for clinical practice

Our findings have several implications for clinical practice. First, the superior success rate and procedural efficiency of the Medtronic LLL system suggest that it is the preferred option for centers implementing LBBAP, particularly during the learning phase. However, the inability to perform continuous unipolar electrogram monitoring using this system is an important limitation that operators should be aware of and compensate for with meticulous fluoroscopic guidance and frequent pacing checks.

Second, the learning curve effect observed in our study underscores the importance of case volume and experience in achieving optimal outcomes with LBBAP.

Third, our finding that advanced age does not negatively affect LBBAP success supports the broader application of this physiological pacing technique, including in older patients who might benefit from avoiding RV pacing-induced cardiomyopathy.

Finally, the specific technical characteristics and limitations of each manufacturer system highlighted in our study can guide operators in adapting their techniques based on the available equipment.

Limitations

Our study had several limitations. First, as this was a sin-

gle-center, single-operator study with a small number of patients, our results may not be generalizable to other centers with different operator expertise or patient populations. In addition, statistical analyses such as propensity score matching or comprehensive multivariate analyses are methodologically desirable, and our relatively limited sample size across some manufacturer groups would compromise the statistical power and reliability of such analyses. Second, the sequential rather than randomized introduction of different manufacturer systems introduces potential confounders through the learning curve effect and temporal trends in patient selection; for example, younger age and fewer comorbidities in the Biotronik group may have influenced our results. Third, we limited our lead-positioning attempts to a maximum of three per patient. If successful lead placement was not achieved within three attempts, the procedure was classified as a failure, and alternative pacing strategies were employed. This approach, while practical and mindful of procedural time and radiation exposure, may have resulted in lower success rates than those achieved with more persistent attempts. Fourth, we did not strictly differentiate between LV septal and LBB pacing in our definition of successful LBBAP. The importance of distinguishing between these subtypes and their respective procedural tactics has gained increasing recognition in recent studies [20,21]. Because our study began in 2021, during the early phase of LBBAP adoption, we did not incorporate these refined classification approaches, which may have influenced our assessment of conduction system capture and overall success rates. However, we did not allow deep septal pacing (DSP) and considered it a failure. In the case of patients with DSP, since the long-term lead safety of DSP is not known, we retrieved the lead from septal placement and changed it to the RV myocardial pacing strategy.

Fifth, we did not systematically assess long-term lead performance parameters, which may differ among manufacturer systems and influence the durability of physiological pacing. The current study design and data collection focused specifically on procedural success rates, acute complications, and technical aspects of implantation across different systems. Finally, we did not evaluate clinical outcomes, such as heart failure hospitalizations or echocardiographic parameters, which would provide insights into the functional impact of successful LBBAP with different systems.

In conclusion, in this comprehensive analysis of 214 LBBAP procedures using four different manufacturer systems, we found significant variations in success rates and procedural characteristics. The Medtronic SelectSecure 3830 LLL system achieved the highest success rate (93.2%) and shortest procedure time despite the limitation of not allowing continuous unipolar electrogram monitoring. A clear learning curve effect was observed, with success rates improving substantially over time in most systems. Patient characteristics, including advanced age, did not significantly affect procedural success, suggesting that LBBAP can be performed effectively in diverse patient populations. These findings provide valuable insights for centers implementing LBBAP and may guide future technological developments in this rapidly evolving field of physiological pacing.

Acknowledgements

None.

Ethics approval

The study protocol was approved by the Institutional Review Board of Keimyung University Dongsan Hospital (approval number: 2021-08-092). All patients provided written informed consent for the procedure and participation in the study, which was conducted in accordance with the Declaration of Helsinki and the Good Clinical Practice guidelines.

Conflict of interest

The authors have nothing to disclose.

Funding

None.

Supplementary materials

Supplementary materials can be found via https://doi.org/10.14802/kmj.2025.00052.

ORCID

Min-Su Jung, https://orcid.org/0000-0002-5699-250X
Jongmin Hwang, https://orcid.org/0000-0001-9710-0945
Tae-Wan Chung, https://orcid.org/0000-0002-9887-6398
Hyoung-Seob Park, https://orcid.org/0000-0002-8042-1029

References

1. Chung MK, Patton KK, Lau CP, Dal Forno ARJ, Al-Khatib SM, Arora V, et al. 2023 HRS/APHRS/LAHRS guideline on cardiac physiologic pacing for the avoidance and mitigation of heart failure. Heart Rhythm. 2023;20:e17–e91.
2. Huang W, Su L, Wu S, Xu L, Xiao F, Zhou X, et al. A novel pacing strategy with low and stable output: pacing the left bundle branch immediately beyond the conduction block. Can J Cardiol. 2017;33:1736.e1–e3.
3. Mirmaksudov M, Ross S, Kongsgård E, Edvardsen T. Enhancing cardiac pacing strategies: a review of conduction system pacing compared with right and biventricular pacing and their influence on myocardial function. Eur Heart J Cardiovasc Imaging. 2024;25:879–87.
4. Yuan Z, Cheng L, Wu Y. Meta-analysis comparing safety and efficacy of left bundle branch area pacing versus his bundle pacing. Am J Cardiol. 2022;164:64–72.
5. Burri H, Jastrzebski M, Cano Ó, Čurila K, de Pooter J, Huang W, et al. EHRA clinical consensus statement on conduction system pacing implantation: endorsed by the Asia Pacific Heart Rhythm Society (APHRS), Canadian Heart Rhythm Society (CHRS), and Latin American Heart Rhythm Society (LAHRS). Europace. 2023;25:1208–36.
6. Vijayaraman P, West M, Dresing T, Oren J, Abbey S, Zimmerman P, et al. Safety and performance of conduction system pacing: real-world experience from a product surveillance registry. Heart Rhythm. 2025;22:318–24.
7. Vijayaraman P, Foo D, Lim TSE, Diamantakos E, Verma S, Hourdain J, et al. Result of the left bundle branch area pacing data collection registry, an international multicenter study of conduction system pacing with a Tendril STS 2088 stylet-driven lead. J Cardiovasc Electrophysiol. 2024;35:1452–60.
8. Friedman DJ, Shadrin I, Goldbarg S, Trulock KM, Patel A, Loring Z, et al. Performance of an active fixation stylet-driven lead in left bundle branch area pacing: results from INSIGHT-LBBA. Heart Rhythm; 2025. https://doi.org/10.1016/j.hrthm.2025.01.041.
9. Liu CF, Prasad KV, Moretta A, Vijayaraman P, Zanon F, Gleva M, et al. Left bundle branch area pacing using a stylet-driven, retractable-helix lead: short-term results from a prospective multicenter IDE trial (the BIO-CONDUCT study). Heart Rhythm. 2024;21:2242–9.
10. Cano Ó, Pooter J, Zanon F. Stylet-driven leads or lumenless leads for conduction system pacing. Arrhythm Electrophysiol Rev. 2024;13:e14.
11. Chapman D, Morgan F, Tiver KD, Dharmaprani D, Jenkins E, Ullah S, et al. Assessing torque transfer in conduction system pacing: development and evaluation of an ex vivo model. JACC Clin Electrophysiol. 2024;10:306–15.
12. Li X, Li H, Ma W, Ning X, Liang E, Pang K, et al. Permanent left bundle branch area pacing for atrioventricular block: Feasibility, safety, and acute effect. Heart Rhythm. 2019;16:1766–73.
13. Upadhyay GA, Cherian T, Shatz DY, Beaser AD, Aziz Z, Ozcan C, et al. Intracardiac Delineation of Septal Conduction in Left Bundle-Branch Block Patterns. Circulation. 2019;139:1876–88.
14. Ponnusamy SS, Ganesan V, Ramalingam V, Syed T, Mariappan S, Murugan S, et al. MAgnetic resonance imaging based DUal lead cardiac Resynchronization therapy: a prospectIve Left Bundle Branch Pacing study (MADURAI LBBP study). Heart Rhythm. 2023;20:1119–27.
15. Do U, Hwang J. Initial experiences of left bundle branch area pacing in Daegu, South Korea–new procedure with familiar tools. Keimyung Med J. 2023;42:27–37.
16. De Pooter J, Wauters A, Van Heuverswyn F, Le Polain de Waroux JB. A guide to left bundle branch area pacing using stylet-driven pacing leads. Front Cardiovasc Med. 2022;9:844152.
17. Tan NY, Witt CM, Oh JK, Cha YM. Left bundle branch block: current and future perspectives. Circ Arrhythm Electrophysiol. 2020;13:e008239.
18. Jastrzębski M, Kiełbasa G, Cano O, Curila K, Heckman L, De Pooter J, et al. Left bundle branch area pacing outcomes: the multicentre European MELOS study. Eur Heart J. 2022;43:4161–73.
19. Pestrea C, Cicala E, Lovin D, Gheorghe A, Ortan F, Manea R. Gender differences for his bundle pacing long-term performance in the elderly population. J Cardiovasc Dev Dis. 2025;12:88.
20. Diaz JC, Tedrow UB, Duque M, Aristizabal J, Braunstein ED, Marin J, et al. Left bundle branch pacing vs left ventricular septal pacing vs biventricular pacing for cardiac resynchronization therapy. JACC Clin Electrophysiol. 2024;10:295–305.
21. Chen J, Ezzeddine FM, Liu X, Vaidya V, McLeod CJ, Valverde AM, et al. Left bundle branch pacing vs ventricular septal pacing for cardiac resynchronization therapy. Heart Rhythm O2. 2024;5:150–7.