

Incidence and predictors of tricuspid regurgitation after left bundle branch area pacing: A Korean multicenter registry study

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ABSTRACT

BACKGROUND Left bundle branch area pacing (LBBAP) is a physiologic pacing strategy encompassing heterogeneous pacing subtypes. However, predictors of clinically significant tricuspid regurgitation (TR) after LBBAP, particularly according to pacing subtype, remain unclear.

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OBJECTIVE To identify the incidence and predictors of significant TR following LBBAP.

METHODS We retrospectively analyzed patients from 31 centers who underwent successful LBBAP between 2021 and 2024 and had no or mild TR at baseline. LBBAP was categorized as left bundle branch pacing, left fascicular pacing, and left ventricular septal pacing (LVSP). The primary outcome was incident TR, defined as new-onset moderate-or-greater TR on follow-up echocardiography performed 6–12 months after the index procedure. Multivariable logistic regression was performed to identify predictors of incident TR.

RESULTS Among 523 patients (mean age, 72.5 ± 11.9 years; 45.5% male), 35 (6.7%) developed incident TR during 1-year follow-up. Compared with patients without incident TR, those with incident TR had a significantly higher prevalence of atrial fibrillation (AF), higher baseline TR maximal velocity (Vmax), longer baseline QRS duration, and a higher frequency of LVSP. On multivariable analysis, AF (odds ratio [OR], 12.55; 95% confidence interval [CI], 3.18–49.55), LVSP (OR, 9.08; 95% CI, 2.35–35.12), baseline TR Vmax of ≥ 2.8 m/second (OR, 4.19; 95% CI, 1.20–14.60), and baseline QRS duration of ≥ 120 ms (OR, 3.80; 95% CI, 1.01–14.32) were independently associated with incident TR.

CONCLUSION Incident TR occurred in 6.7% of patients following successful LBBAP. LVSP, prevalent AF, elevated TR Vmax, and prolonged QRS duration were independent predictors of incident TR.

KEYWORDS Conduction system pacing; Left bundle branch area pacing; Predictor; Retrospective cohort; Tricuspid regurgitation

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Left bundle branch area pacing (LBBAP) has emerged as a promising physiologic strategy to mitigate the risk of pacing-induced heart failure associated with conventional right ventricular pacing and as a potential alternative to cardiac resynchronization therapy.^{1–3} Tricuspid regurgitation (TR) is a well-documented complication of transvenous pacing.^{4,5} Because new-onset significant TR may contribute to long-term morbidity and mortality, prediction and prevention of TR in patients undergoing LBBAP are of considerable clinical importance.

Whether LBBAP can prevent or aggravate TR remains controversial. Although LBBAP is expected to reduce TR risk by preserving right ventricular synchrony, the potential for mechanical lead–leaflet interaction remains a concern. Indeed, clinically significant TR has been reported in a substantial number of patients following LBBAP.⁶ Unlike conventional right ventricular pacing, LBBAP requires lead fixation at the proximal interventricular septum. This anatomical positioning places the lead closer to the tricuspid annulus, potentially increasing susceptibility to the development or progression of TR.^{7,8} In contrast, Chen et al⁹ suggested that the degree of TR could be decreased with LBBAP. This finding implies that the innate risk of TR from a lead crossing the tricuspid valve may be mitigated by the improved hemodynamic response afforded by physiologic ventricular activation. Therefore, identifying the clinical and procedural factors associated with an increased risk of incident TR warrants further investigation to optimize patient selection and refine implantation strategies.

Accordingly, the present study aimed to report the incidence of and identify clinical and procedural predictors of incident moderate-or-greater TR following successful LBBAP.

Methods

Study population and design

This study used a multicenter retrospective registry of patients who underwent LBBAP at 31 centers in the Republic of Korea between 2021 and 2024. A full list of the partici-

pating centers and investigators is presented in [Supplemental Table 1](#).

Of the 2215 patients enrolled in the registry with 1-year follow-up, those who underwent successful LBBAP for the *de novo* device implantation were included in this analysis. Patients were excluded based on the following criteria: (1) no available baseline echocardiography ($n = 124$); (2) more than mild TR at baseline or missing records for TR severity ($n = 31$); (3) missing records for LBBAP failure ($n = 156$); (4) missing records for LBBAP subtype ($n = 132$); (5) no available follow-up echocardiography ($n = 1239$); and (6) missing records for TR severity at follow-up ($n = 10$). The patient selection process is detailed in [Supplemental Figure 1](#).

Preprocedural variables

Preprocedural variables were obtained within 1 month before device implantation and included age, sex, and comorbidities (hypertension, diabetes mellitus, dyslipidemia, atrial fibrillation [AF], coronary artery disease, heart failure, and ischemic stroke). Significant valvular heart disease was defined as moderate-or-greater stenosis or regurgitation of the aortic or mitral valves. Prior valvular interventions included repair, replacement, or annuloplasty of the mitral, tricuspid, or aortic valves. Baseline medication use, including antiarrhythmics, beta-blockers, renin–angiotensin–aldosterone system blockers, mineralocorticoid receptor antagonists, sodium–glucose cotransporter 2 (SGLT2) inhibitors, and diuretics, was recorded. Baseline electrocardiographic and echocardiographic parameters included QRS duration, left atrial volume index (LAVI), and TR maximal velocity (TR Vmax). N-terminal pro-B-type natriuretic peptide (NT-proBNP) levels were also assessed.

Criteria for successful LBBAP and LVSP classification

This study followed the criteria for LBBAP and LVSP classification based on the 2023 European Heart Rhythm Association

(EHRA) consensus document.¹⁰ The gold standard for left bundle branch capture was a QRS transition to LVSP or to selective left bundle branch pacing (LBBP) during decremental output with unipolar pacing. The auxiliary criteria (the presence of any of which supported a diagnosis of LBBAP) were as follows: (1) a V6 R-wave peak time (V6RWPT) of <75 ms in patients with a normal QRS complex or isolated RBBB, or <80 ms in those with LBBB, IVCD, or RBBB with fascicular block; (2) a V6–V1 interpeak interval of >44 ms; (3) a difference within 10 ms between the LBB potential-to-V6RWPT and the stimulus-to-V6RWPT; and (4) a QRS transition to selective LBBP during programmed stimulation. LVSP was defined as pacing lead deployment in the deep septum with a Qs, QR, or qR pattern in lead V1.

Procedural parameters

Procedural parameters were collected at the end of the procedure, including LBBAP success or failure, V6RWPT, unipolar-paced QRS duration, lead type (lumenless vs stylet-driven), and device type (single- or dual-chamber pacemaker, implantable cardioverter-defibrillator [ICD], or LBBAP-optimized cardiac resynchronization therapy [LOT-CRT]). In this study, no defibrillation-capable conduction system lead was used; therefore, ICD implantation was performed by placing a separate high-voltage lead at the right ventricular apex in addition to the ventricular pacing lead for LBBAP. For LOT-CRT-D, a DF-1 system was used, and the high-voltage lead was placed in addition to the left ventricular pacing and LBBAP leads. In LOT-CRT-P, the additional left ventricular lead was placed via the coronary sinus, without an additional trans-tricuspid lead. LBBAP subtypes were classified as LBBP; left posterior, anterior, and septal fascicular pacing (LPFP, LAFP, and LSFP, respectively); or left ventricular septal pacing (LVSP).

Postprocedural assessment and definition of incident TR

Postprocedural assessments, performed at 6 and 12 months (± 3 months), included TR severity, NT-proBNP levels, and ventricular pacing burden. The primary outcome was incident TR, defined as new-onset moderate-or-greater TR on follow-up echocardiography performed 6–12 months after the index procedure.¹¹ This diagnosis was made using a comprehensive 2-dimensional and Doppler echocardiographic evaluation and was based on a combination of quantitative parameters, including a jet area of >5 cm², vena contracta width of >0.7 cm, and proximal isovelocity surface area radius of >5 mm. TR severity was assessed by an independent imaging specialist at each center. The first diagnosed episode of moderate-or-greater TR during the study period was defined as the primary outcome, regardless of subsequent changes.

Statistical analysis

The study population was categorized into 2 groups based on incident TR status: patients with incident TR ($n = 35$) and those without incident TR ($n = 488$). Continuous variables were compared using Student's *t*-test or the Mann–

Whitney U test, as appropriate, based on data distribution. Categorical variables were compared using Fisher's exact test.

Univariable and multivariable logistic regression analyses were performed to evaluate associations between clinical and procedural variables and incident TR. Associations were expressed as odds ratios (ORs) with 95% confidence intervals (CIs). Variables with significant clinical relevance were assessed in the univariable logistic regression model, including AF, significant valvular heart disease, history of valvular heart surgery, use of SGLT2 inhibitors, diuretics, NT-proBNP, LAVI, TR Vmax, baseline QRS duration, LBBAP subtype, V6RWPT, paced QRS duration, and ventricular pacing burden at 1 year. Among these variables, baseline QRS duration and TR Vmax were dichotomized at thresholds of ≥ 120 ms and ≥ 2.8 m/second, respectively.

Multivariable logistic regression analysis was performed using a forward conditional selection method, considering clinically relevant variables that were statistically significant in univariable analysis. The relative contribution of each independent predictor was assessed using likelihood ratio tests by comparing the full multivariable model with reduced models excluding each variable individually. An alternative multivariable model using dichotomized covariates was constructed to enhance clinical interpretability and to assess the robustness of the associations observed in the primary continuous-variable model. Cutoff values for dichotomization were determined based on clinical relevance and the Youden index. The selected cutoffs were 400 pg/mL for NT-proBNP, 34 mL/m² for LAVI, 90 ms for left ventricular activation time, 120 ms for paced QRS duration, and $\geq 90\%$ for ventricular pacing burden at 1 year. Model calibration was assessed using the Hosmer–Lemeshow goodness-of-fit test, and multicollinearity among covariates was evaluated by calculating variance inflation factors.

Subgroup analyses were performed according to baseline AF status (present vs absent). *P*-values for interaction were calculated to assess potential effect modification by baseline AF status.

Two sensitivity analyses were conducted to minimize confounding related to valvular pathology. The first excluded patients with significant valvular heart disease at baseline, whereas the second excluded patients with any history of valvular heart surgery.

All statistical analyses were performed using IBM SPSS Statistics for Windows version 31.0 (IBM Corp.). Graphs were generated using Prism version 11.0 (GraphPad Software). A 2-sided *P*-value of <.05 was considered statistically significant.

Results

Baseline characteristics

With the prespecified inclusion and exclusion criteria, a total of 523 patients with successful LBBAP and no or mild baseline TR comprised the final study cohort. Among these, 35 (6.7%) developed incident TR at 1-year follow-up. Baseline

characteristics of the study population are summarized in Table 1. The mean age was 72.5 ± 11.9 years, and 45.5% were male. No significant differences were observed be-

tween patients with and without incident TR regarding age, sex, implanted device type, pacing indication, or 1-year ventricular pacing burden. Compared with patients who did not

Table 1 Baseline characteristics of the study participants

Variables	Patients without incident TR (n = 488)	Patients with incident TR (n = 35)	P-value
Age	72.4 ± 12.1	74.5 ± 9.8	.315
Men	220 (45.1)	18 (51.4)	.467
Comorbidities			
Hypertension	307 (62.9)	21 (60.0)	.731
Diabetes mellitus	178 (36.5)	15 (42.9)	.450
Dyslipidemia	218 (44.7)	18 (51.4)	.438
Atrial fibrillation	93 (19.1)	21 (60.0)	<.001
Coronary artery disease	107 (21.9)	7 (20.0)	.786
Ischemic stroke	43 (8.8)	2 (5.7)	.528
Significant valvular heart disease	122 (25.0)	15 (42.9)	.020
History of valvular heart surgery	94 (19.3)	14 (40.0)	.003
Heart failure	147 (30.1)	11 (31.4)	.871
Hemodialysis	21 (4.3)	3 (8.6)	.353
Medication			
Antiarrhythmic drug	27 (5.5)	3 (8.6)	.456
Beta blocker	133 (27.3)	13 (37.1)	.208
RAAS blocker	245 (50.2)	20 (57.1)	.428
MRA	72 (14.8)	6 (17.1)	.702
SGLT2 inhibitor	61 (12.5)	1 (2.9)	.089
Diuretics	126 (25.8)	16 (45.7)	.011
Baseline laboratory tests			
NT-proBNP, pg/mL	702 (205–2441)	1821 (597–8851)	.008
LVEF, %	57.8 ± 13.0	56.9 ± 13.1	.714
LAVI, cc/m ²	42.1 (32.9–56.9)	56.7 (41.2–86.7)	<.001
TR Vmax, m/s	2.6 ± 0.4	2.9 ± 0.6	.008
QRS duration, ms	124.4 ± 32.3	133.9 ± 28.6	.091
Procedural data			
Lead type			.167
LLL	25 (5.1)	0 (0.0)	
SDL	456 (93.4)	35 (100.0)	
Unknown	7 (1.4)	0 (0.0)	
LBBAP subtype			.001
Other than LVSP	413 (84.6)	22 (62.9)	
Left bundle branch pacing	226 (46.3)	14 (40.0)	
Left posterior fascicular pacing	126 (25.8)	6 (17.1)	
Left anterior fascicular pacing	44 (9.0)	0 (0.0)	
Left septal fascicular pacing	17 (3.5)	2 (5.7)	
LVSP	75 (15.4)	13 (37.1)	
V6RWPT, ms	75 (67–84)	80 (75–91)	.020
Paced QRS duration, ms	117.7 ± 19.1	124.3 ± 16.8	.047
Device type			.531
Pacemaker	448 (91.8)	30 (85.7)	
ICD	10 (2.0)	0 (0.0)	
LOT-CRT	24 (4.9)	1 (2.9)	
Others/unknown	6 (1.2)	4 (11.4)	
Procedure indication			.682
Sinus node dysfunction	56 (11.5)	6 (17.1)	
AF SVR	31 (6.4)	4 (11.4)	
AVB	353 (72.3)	19 (54.3)	
Heart failure	33 (6.8)	4 (11.4)	
Others	15 (3.1)	2 (5.7)	
Ventricular pacing burden at 1 year, %	99 (94–100)	98 (65–100)	.071

Data are presented as n (%), mean $\pm$ standard deviation, or median (interquartile range).

AF SVR = atrial fibrillation with slow ventricular response; AVB = atrioventricular block; ICD = implantable cardioverter-defibrillator; LAVI = left atrial volume index; LBBAP = left bundle branch area pacing; LLL = lumenless lead; LOT-CRT = LBBAP-optimized cardiac resynchronization therapy; LVEF = left ventricular ejection fraction; LVSP = left ventricular septal pacing; MRA = mineralocorticoid receptor antagonist; NT-proBNP = N-terminal pro-B-type natriuretic peptide; RAAS = renin-angiotensin-aldosterone system; SDL = stylet-driven lead; SGLT2 = sodium glucose cotransporter 2; TR = tricuspid regurgitation; V6RWPT = V6 R-wave peak time.

develop incident TR, those with incident TR exhibited a significantly higher prevalence of AF (60.0% vs 19.1%), significant underlying valvular heart disease (42.9% vs 25.0%), and prior valvular heart surgery (40.0% vs 19.3%). Detailed information on underlying valvular heart disease and prior valvular heart surgery is presented in [Supplemental Table 2](#). Furthermore, the incident TR group was characterized by higher NT-proBNP levels (median 1821 vs 702 pg/mL), larger left atrial volume index (median 56.7 vs 42.1 mL/m²), and higher TR Vmax (2.9 vs 2.6 m/second). Notably, a greater proportion of patients with incident TR underwent LVSP than those without incident TR (37.1% vs 15.4%). Regarding lead type, 5.1% of patients without incident TR received lumenless leads, whereas none of those with incident TR did.

Clinical courses of the patients with incident TR

Among the 35 patients with incident significant TR, 26 developed moderate TR and 9 developed severe TR, corresponding to a 1-year incidence of newly developed severe TR of 1.7%. During the 1-year follow-up period, no lead or device revisions were performed, and TR was managed conservatively. Heart failure hospitalization occurred in 5 patients, and cardiovascular death occurred in 1 patient.

Predictors of incident TR

Logistic regression analysis was performed to evaluate the association between LBBAP subtypes and incident TR. The results are presented in [Supplemental Table 3](#). Among the LBBAP subtypes, only LVSP was significantly associated with incident TR. Compared with patients who underwent other LBBAP subtypes, those who underwent LVSP exhibited a significantly longer paced QRS duration (127 ± 20 ms vs 116 ± 18 ms; $P < .001$).

Results of univariable and multivariable logistic regression analyses are presented in [Table 2](#). In univariable analysis, prevalent AF, LVSP, baseline TR Vmax of ≥ 2.8 m/second,

baseline QRS duration of ≥ 120 ms, significant underlying valvular heart disease, history of valvular heart surgery, diuretic use, and ventricular pacing burden at 1 year were significantly associated with incident TR. In the multivariable model, prevalent AF (OR, 12.55; 95% CI, 3.18–49.55), LVSP (OR, 9.08; 95% CI, 2.35–35.12), baseline TR Vmax of ≥ 2.8 m/second (OR, 4.19; 95% CI, 1.20–14.60), and baseline QRS duration of ≥ 120 ms (OR, 3.80; 95% CI, 1.01–14.32) remained independently associated with incident TR ([Figure 1](#)). Among the independent predictors, prevalent AF showed the greatest contribution to model fit on likelihood ratio testing, followed by LVSP, whereas electrocardiographic and echocardiographic parameters demonstrated more modest incremental contributions ([Supplemental Table 4](#)).

In univariable analysis stratified by AF type, both paroxysmal and persistent AF were significantly associated with incident TR, with higher odds observed for persistent AF (OR, 5.91; 95% CI, 2.52–13.85) than for paroxysmal AF (OR, 3.34; 95% CI, 1.58–7.02) ([Supplemental Table 5](#)).

Subgroup analyses according to baseline AF status

Subgroup analyses stratified by the presence of prevalent AF were performed, and the results are presented in [Supplemental Tables 6 and 7](#). Among patients with AF ($n = 114$), multivariable logistic regression analysis identified LVSP as the only variable independently associated with incident TR (OR, 7.29; 95% CI, 1.77–35.57; $P = .007$). In contrast, among patients without prevalent AF ($n = 409$), baseline TR Vmax of ≥ 2.8 m/second showed a marginal association with incident TR (OR, 3.23; 95% CI, 0.95–10.95; $P = .060$), whereas no other variables were statistically significant.

Sensitivity analyses

Sensitivity analyses excluding patients with significant valvular heart disease or a history of valvular heart surgery are shown in [Figure 2](#). These analyses yielded results

Table 2 Comparison between univariable and multivariable analyses

Variables	Univariable model		Multivariable model	
	OR (95% CI)	P-value	OR (95% CI)	P-value
Baseline atrial fibrillation	6.37 (3.12–13.00)	<.001	12.55 (3.18–49.55)	<.001
LVSP	3.25 (1.57–6.74)	.002	9.08 (2.35–35.12)	.001
Baseline QRS duration ≥ 120 ms	1.74 (0.85–3.57)	.133	4.19 (1.20–14.60)	.024
Baseline TR Vmax ≥ 2.8 m/s	2.92 (1.42–6.00)	.004	3.80 (1.01–14.32)	.048
Significant valvular heart disease	2.25 (1.12–4.53)	.023	-	-
History of valvular heart surgery	2.79 (1.37–5.70)	.005	-	-
SGLT2 inhibitor	0.21 (0.03–1.53)	.123	-	-
Diuretics	2.42 (1.21–4.85)	.013	-	-
Baseline NT-proBNP, pg/ml	1.00 (1.00–1.00)	.161	-	-
Baseline LAVI, cc/m ²	1.00 (1.00–1.00)	.608	-	-
V6RWPT, ms	1.03 (1.00–1.05)	.043	-	-
Paced QRS duration ≥ 120 ms	1.59 (0.79–3.17)	.194	-	-
Ventricular pacing burden at 1 year, %	0.99 (0.98–1.00)	.028	-	-

The univariable and multivariable logistic regression analyses were performed with enter and forward conditional selection methods, respectively.

CI = confidence interval; LAVI = left atrial volume index; LVSP = left ventricular septal pacing; NT-proBNP = N-terminal pro-B-type natriuretic peptide; OR = odds ratio; SGLT2 = sodium glucose cotransporter 2; TR = tricuspid regurgitation; V6RWPT = V6 R-wave peak time.

Predictors	OR (95% CI)	p-value
Atrial fibrillation	12.55 (3.18–49.55)	<0.001
LVSP	9.08 (2.35–35.12)	0.001
TR Vmax ≥ 2.8 m/s	4.19 (1.20–14.60)	0.024
QRS duration ≥ 120 ms	3.80 (1.01–14.32)	0.048

Figure 1

Predictors for incident tricuspid regurgitation (TR) at 1 year after left bundle branch area pacing (LBBAP). After multivariable logistic regression analyses, baseline atrial fibrillation, left ventricular septal pacing, baseline TR Vmax of ≥ 2.8 m/second, and baseline QRS duration of ≥ 120 ms were significant predictors of incident TR at 1 year. The full list of covariates is presented in Table 2. CI = confidence interval; LBBAP = left bundle branch area pacing; LVSP = left ventricular septal pacing; OR = odds ratio; TR = tricuspid regurgitation.

consistent with the primary analysis, confirming that prevalent AF, LVSP, and baseline QRS duration of ≥ 120 ms remained significant predictors of incident TR. Likelihood ratio testing indicated that AF and LVSP accounted for most of the model's explanatory power (Supplemental Table 8).

An additional sensitivity analysis using dichotomized covariates in the multivariable logistic regression model is presented in Supplemental Table 9. Consistent with the primary findings, AF and LVSP remained significantly associated with incident TR.

Discussion

This study is a comprehensive multicenter investigation of the clinical and procedural predictors of incident moderate-or-greater TR following successful LBBAP. The principal findings are as follows. First, incident TR was detected in 6.7% of patients on 1-year follow-up echocardiography. Second, prevalent AF, LVSP subtype, TR Vmax of ≥ 2.8 m/second, and baseline QRS duration of ≥ 120 ms were identified as independent predictors of incident TR within 1 year of implantation. Third, subgroup analyses re-

vealed distinct predictive profiles according to AF status; specifically, LVSP was the sole independent predictor in patients with AF, whereas a higher baseline TR Vmax was the primary factor associated with incident TR in those without AF. These results identify specific clinical and procedural characteristics, particularly the presence of AF and the LVSP subtype, that are associated with an increased risk of incident TR in patients undergoing LBBAP.

TR in the era of the conduction system pacing

TR is a well-recognized complication of cardiac implantable electronic devices. Patients with a cardiac implantable electronic device have a 65% higher risk of TR, with a significant TR incidence of 4.6% annually.^{12,13} Potential mechanisms include direct lead–valve interaction and pacing-related heart failure, leading to right ventricular remodeling and tricuspid annular dilation.^{14–17}

Conduction system pacing has been introduced to achieve more physiologic ventricular activation and to improve ventricular function compared with conventional right ventricular pacing. Recent evidence has demonstrated that conduction system pacing is associated with a significantly lower risk of TR progression than right ventricular pacing, presumably by restoring physiologic ventricular activation.¹⁸ Accordingly, LBBAP was expected to mitigate pacing-induced TR.

In our registry, the incidence of incident TR was 6.7%, which is lower than previously reported rates of significant TR following conventional right ventricular apical pacing, consistent with the findings of Su et al.¹⁹ This lower incidence may relate to the more physiologic ventricular activation achieved with LBBAP, although the precise mechanisms are uncertain. Our findings are also limited by the relatively short follow-up; thus, longer-term data from larger prospective registries are needed to validate these observations.

The prevalence of TR progression varies widely by pacing modality. Compared with biventricular pacing, right ventricular pacing has been associated with a higher prevalence of TR progression (17.4% vs 9.8%).²⁰ Compared with LBBAP, leadless pacemaker implantation or right ventricular pacing

Predictors	Excluding significant VHD at baseline		Excluding any history of VHS	
	OR (95% CI)	p-value	OR (95% CI)	p-value
Atrial fibrillation	22.41 (3.35–149.90)	0.001	34.06 (5.09–228.09)	<0.001
LVSP	22.51 (3.89–130.43)	0.002	18.09 (3.23–101.37)	0.001
QRS duration ≥ 120 ms	10.68 (1.49–76.46)	0.018	11.56 (1.73–77.23)	0.012

Figure 2

Sensitivity analyses. The sensitivity analyses were performed using multivariable logistic regression. Baseline atrial fibrillation, left ventricular septal pacing, and baseline QRS duration of ≥ 120 ms were significant predictors of incident tricuspid regurgitation at 1 year. The full list of covariates is presented in Table 2. CI = confidence interval; LBBAP = left bundle branch area pacing; LVSP = left ventricular septal pacing; OR = odds ratio; TR = tricuspid regurgitation; VHD = valvular heart disease; VHS = valvular heart surgery.

may be associated with a more than 2-fold increased risk of worsening TR.²¹ Recent studies suggest that, compared with right ventricular pacing, LBBAP may reduce heart failure aggravation and mortality.^{22,23} Although direct comparison is limited by differences in study populations, TR definitions, and follow-up duration, the 6.7% incidence of significant TR observed in our LBBAP cohort appears to fall within or below the range reported for conventional pacing modalities. Nevertheless, TR remains a clinically relevant issue in the contemporary era.

Prior studies have reported that TR deterioration may occur in approximately 33% of patients following LBBAP.²⁴ The risk of TR after LBBAP is partly attributable to the shorter distance between the lead implantation site and the tricuspid valve, which may increase mechanical interference with the tricuspid valve apparatus.⁷ In addition, LBBAP encompasses heterogeneous pacing subtypes with distinct electrophysiological and mechanical characteristics. Among these, LVSP has been associated with a higher incidence of heart failure and less favorable clinical outcomes compared with LBBP.^{25,26} Despite these concerns, successful LBBP may not always be achievable owing to patient-specific factors or underlying structural heart disease, and LVSP continues to account for approximately 21.5% of LBBAP procedures in contemporary practice.²⁷

Interpretation of predictors identified in the present study

The present study extends prior observations by identifying both patient-related and procedural predictors of incident TR following LBBAP. AF emerged as the strongest independent predictor of incident TR, and the higher odds observed in patients with persistent AF further support the association between advanced atrial remodeling and TR vulnerability (Supplemental Table 5).

LVSP was another independent predictor of incident TR, with a particularly strong association among patients with AF. However, the mechanisms linking LVSP to incident TR remain uncertain, and this finding should be regarded as hypothesis-generating and warranting prospective studies with advanced electrophysiological and echocardiographic assessments.^{28,29}

The patients receiving LVSP had a significantly larger baseline left ventricular end-diastolic diameter (Supplemental Table 10) and a higher prevalence of significant valvular heart disease and prior valvular heart surgery (Supplemental Table 11). These findings suggest that LVSP may have been more frequently accepted in patients with structural heart disease or greater procedural complexity. However, exploratory analyses showed no significant differences in left ventricular ejection fraction or left ventricular dimensions at 1-year follow-up between patients with LVSP and those with other LBBAP subtypes (Supplemental Table 10). Therefore, our data do not support deterioration in left ventricular systolic function as the primary explanation for the association between LVSP and incident TR. Although this association persisted in sensitivity analyses excluding pa-

tients with underlying valvular heart disease (Figure 2), residual confounding by baseline structural heart disease or procedural factors cannot be excluded. Accordingly, the association between LVSP and incident TR should be interpreted with caution, given that the underlying mechanism remains uncertain.

Also, the higher prevalence of LVSP among patients with incident significant TR warrants careful interpretation. Because of the retrospective design, the procedural reasons for accepting LVSP were not systematically recorded; however, LVSP was more likely to represent a suboptimal result when true LBBP could not be achieved than an intentional target. Consistent with this, an indirect review of lead deployment attempts suggested that a numerically higher proportion of patients with incident TR required multiple attempts, although this was limited by substantial missing data and should be regarded as hypothesis-generating. Importantly, these procedures were performed between January 2021 and December 2024, when data on the potential inferiority of LVSP to LBBP—particularly in structural heart disease or heart failure—were limited, and the cohort included early learning-curve cases. Factors that impede true LBBP capture, including structural heart disease, a diseased conduction system, and cardiomegaly, may co-occur and confound the association. These factors may collectively contribute to TR, or LVSP itself may contribute, and the 2 cannot be separated in our data.

Although the sensitivity analyses excluding patients with valvular heart disease or prior valvular surgery were consistent with the primary analysis, the number of events in these analyses was small, yielding wide CIs and reduced precision. In addition, patients with incident significant TR had higher baseline NT-proBNP levels and LAVI. Although neither was independently associated with incident TR in regression analyses (Table 2), these baseline differences may reflect more advanced underlying cardiac disease. Therefore, residual confounding related to baseline cardiac disease severity cannot be excluded, particularly given the retrospective design and limited number of events.

Our results may also be affected by the high prevalence of stylet-driven lead use over lumenless leads. In Korea, stylet-driven leads were introduced for LBBAP a couple of years earlier than lumenless leads, which differs from the sequence of market introduction in other countries. Consequently, the current cohort inevitably included a higher proportion of stylet-driven leads, and operator experience was largely accumulated with stylet-driven leads before lumenless leads were adopted. Recent studies have suggested that the efficacy and safety of stylet-driven leads for LBBAP may be comparable to those of lumenless leads.^{30–34} However, stylet-driven leads have distinct structural characteristics from lumenless leads, including greater lead thickness and an extendable-retractable screw mechanism, or differences in the landing zone by their own property, which may influence procedural outcomes. Therefore, the possibility that lead types contributed to our findings cannot be entirely ruled out.

Given that AF can promote functional TR through atrial and annular remodeling, we further explored differences in predictive profiles by AF status. Consistent with prior reports,³⁵ persistent AF carried a higher OR for incident TR than paroxysmal AF (Supplemental Table 5). In patients without AF, baseline TR Vmax emerged as the primary predictor of subsequent TR progression (Supplemental Table 7), suggesting that pre-existing right-heart hemodynamic burden may increase risk independent of AF. In contrast, among patients with AF, LVSP was the sole significant predictor (Supplemental Table 6), suggesting a greater contribution of pacing-related hemodynamic disadvantage in patients with atrial cardiomyopathy. These findings support an AF-stratified risk assessment approach and may inform procedural strategies to mitigate TR after LBBAP.

Baseline QRS prolongation and elevated TR Vmax were also independently associated with incident TR. Prolonged baseline QRS duration and elevated TR Vmax may identify patients with pre-existing conduction or right-heart abnormalities at higher risk of incident TR.

Collectively, these findings indicate that TR development after LBBAP is a multifactorial process influenced by baseline cardiac substrate, ventricular conduction profiles, and pacing subtype. Consideration of these factors may help optimize patient selection and implantation strategies to mitigate the risk of TR progression in patients undergoing LBBAP.

Limitations

This study has several limitations to be acknowledged. First, the retrospective design of this multicenter study introduces the potential for selection bias and residual confounding, particularly because a substantial proportion of the original cohort was excluded due to missing follow-up echocardiographic data. First, the retrospective design of this multicenter study introduces the potential for selection bias and residual confounding, particularly because a substantial proportion of the original cohort (1239 of 2215 patients, 55.9%) was excluded owing to the unavailability of follow-up echocardiography. In addition, the limited number of incident TR events resulted in wide CIs for several predictors, indicating limited precision. Accordingly, the magnitude of the reported associations should be interpreted with caution. Causal relationships between identified predictors and incident TR cannot be established, and the findings warrant validation in prospective studies. Second, AF burden and TR severity may evolve during follow-up in response to changes in medical therapy or post-procedural management. Owing to the inherent limitations of registry data, longitudinal changes in these parameters could not be systematically assessed. Third, although a shorter distance between the lead and the tricuspid annulus has been reported as a risk factor for TR after LBBAP,⁷ this distance was not prospectively assessed in a standardized imaging view in our registry. In a retrospective exploratory analysis conducted in a subset of patients, the lead-annulus distance was 20 mm (IQR, 16–25 mm) based on heterogeneous echocardiographic or fluoroscopic measurements, and it showed no clear association

with incident TR. However, given these methodological constraints, this finding should not be interpreted as evidence for or against such a relationship, which warrants dedicated prospective studies using standardized imaging. Fourth, the effect of lead type on incident TR could not be evaluated because no patients with incident TR received lumenless leads, precluding meaningful logistic regression analysis. The low prevalence of lumenless lead use likely reflects its late market introduction in Korea, which limited the number of patients with 1-year follow-up data. Similarly, the association between the number of implanted leads and incident TR could not be analyzed using the current database. Fifth, because our registry enrolled only patients who underwent LBBAP and did not include conventional pacing modalities, a direct comparison of TR incidence with right ventricular apical or biventricular pacing was not feasible, and such comparisons in our discussion rely on prior literature. An unbiased comparison would ideally require propensity-score matching against contemporaneously and uniformly assessed RV apical or biventricular pacing cohorts; however, as LBBAP is already in widespread clinical use, a contemporaneous conventional-pacing comparator free of selection bias would require a prospective randomized trial. Sixth, the mechanisms by which LVSP may promote incident TR remain incompletely understood, and detailed physiological assessments were not available. Additionally, confounding by indication—whereby LVSP was selectively performed in patients who failed to achieve true left bundle branch capture—cannot be fully excluded despite the sensitivity analyses. Moreover, the predominance of early-era and learning-curve procedures, as well as unmeasured factors that hinder the true left bundle branch capture (such as structural heart disease, a diseased conduction system, and cardiomegaly), may further confound this association. Future studies using advanced electrophysiological and imaging modalities are needed to clarify the mechanisms linking LVSP to TR progression. Seventh, an additional high-voltage, trans-tricuspid lead may aggravate TR, but its effect could not be adequately evaluated because only a small, non-substantial proportion of patients received such a lead (ICD, $n = 10$; LOT-CRT-D, $n = 7$; 17 of 523, 3.3% in total). Lastly, LBBAP subtype classification was based on operator-reported procedural and electrocardiographic findings, and no independent core laboratory or blinded adjudication of post-procedural ECGs was performed. In addition, subtype classification followed the 2023 EHRA consensus criteria¹⁰ available at the time of the procedures, most of which preceded publication of the 2025 European Society of Cardiology consensus document.¹ Although the 2 documents share the same core diagnostic principle, the 2025 consensus places greater emphasis on the transition in QRS morphology during decremental unipolar output to confirm left bundle branch capture. Because the procedural data required to apply these refined criteria were not systematically captured at implantation, retrospective re-adjudication of LBBAP subtype was not feasible, and misclassification between LBBP and LVSP cannot be fully excluded. As the criteria for

identifying true left bundle branch capture continue to evolve, prospective large-scale studies applying the stricter 2025 criteria are warranted to clarify the relationship between LBBAP subtype and incident TR.

Conclusion

In this multicenter retrospective study, incident TR was detected in 6.7% of patients on 1-year follow-up echocardiography. Prevalent AF, LVSP, elevated TR Vmax, and prolonged baseline QRS duration were independently associated with incident TR within 1 year after successful LBBAP. Notably, the association between LVSP and incident TR appeared more pronounced in patients with underlying AF. These findings suggest that careful patient selection and meticulous implantation strategy, particularly avoidance of LVSP when feasible, may be warranted in high-risk patients to mitigate the development or progression of TR following LBBAP.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the authors used ChatGPT 5.4 only to check grammar. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the published article.

Data sharing statement

The data underlying this article will be shared on reasonable request to the corresponding author.

Appendix

Supplementary data

Supplementary data associated with this article can be found in the online version at <https://doi.org/10.1016/j.hrthm.2026.07.031>.

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