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Conduction system pacing: promoting the physiology to prevent heart failure

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Abstract

Cardiac conduction system pacing provides physiological ventricular activation by directly stimulating the conduction system. This review describes the two types of conduction system pacing: His bundle pacing (HBP) and left bundle area pacing (LBAP). The most significant advantage of HB pacing is that it can provide a regular, narrow QRS; however, the disadvantages are challenging implantation and a high risk of re-intervention due to lead dislodgement and the development of high pacing threshold. LBAP provides optimum physiological activation of the left ventricle by engaging the left bundle/fascicular fibers. LBAP is more physiological than traditional RV apical pacing and could be an attractive alternative to conventional cardiac resynchronization therapy (CRT). The advantages of LBAP are a relatively more straightforward implantation technique than HBP, better lead stability and pacing thresholds. HBP and LBAP are more physiological than right ventricular pacing and may be used instead of conventional pacemakers. Both HBP and LBBP are being investigated as alternatives to conventional CRT.

Keywords His bundle pacing · Left bundle area pacing · Cardiac resynchronization · Heart failure

Introduction

Conventional cardiac resynchronization therapy (CRT) is an essential part of treating selected patients with HFrEF and ventricular dyssynchrony due to wide QRS. However, conventional CRT requires implantation of an extra lead in the coronary sinus, which sometimes may be challenging and less feasible due to unsuitable anatomy, phrenic nerve stimulation, and unacceptably high local thresholds. Moreover, the left ventricular epicardial stimulation may not

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entirely resolve the electrical dyssynchrony [1, 2]. Epicardial placement of LV lead has been suggested as an alternative method in the case of transvenous procedure failure during CRT device implantation, but it may cause lead failure and rather highly reported complications such as infection [5].

These challenges with conventional CRT led to the development of a new concept of pacing—the conduction system pacing (namely His bundle pacing (HBP) and left bundle area pacing (LBAP)), which can also be alternatives to conventional right ventricular pacing in selected patients.

Clinical anatomy of physiological pacing

The His bundle (HB) is a thin structure penetrating the central fibrous body of the heart and has two main anatomical variants. The type I HB, present in 46.7% of subjects, when the AV bundle is covered by a thin layer of myocardial fibers and runs along the lower border of the membranous septum. Conversely, the type II HB runs within the muscular part of the interventricular septum below the pars membranacea [2, 3]. Both atrial and ventricular portions of the HB can be accessed for permanent conduction system pacing [1]. The HB has significant positional variations relative to the membranous septum [1], influencing selective His bundle pacing (S-HBP) or nonselective His bundle pacing (NS-HBP) during permanent HBP procedure.

LBB's anatomical features determine the feasibility of LBBP as a potential physiological pacing modality. In contrast to HBP, LBBP that is determined by the capture of the LBB and distal conduction system tissues has a much wider target zone for area pacing that is likely to be beyond the site of the block in distal HB [5]. In contrast to right ventricular apical pacing, HBP does not induce interventricular or intraventricular asynchrony and does not provoke myocardial perfusion disorders [6].

Development and early experience of human HBP and LBBP

Implementing physiological pacing techniques directly activating the conduction system has been and continues to be a crucial issue in managing cardiac conduction disease. Hence, electrophysiological challenges arose as development progressed. Nearly 5 decades ago Narula et al. reported that the pacing impulse to ventricular activation time (PI-R) during the procedure was the same as the H-V time during normal sinus rhythm [7]. Subsequently, the ability of HBP to generate truly physiological ventricular activation would allow this technique to become a full-fledged alternative to cardiac resynchronization therapy (CRT) [8] and has been recommended as a rescue modality for failed biventricular pacing [9].

Since 2006, several reports which described the use of HBP in clinical practice have been published [10]. These reports have led to further investigation of the effectiveness of permanent HBP in patients requiring pacing and device-paced HF therapy [11]. After that, the benefits of permanent HBP were proved in multiple studies. In particular, the first systematic analysis of a large pool of patients demonstrated a high success for HBP concerning the sustaining of cardiac function with the potential for significant improvement in LVEF in patients with systolic dysfunction and heart failure [12].

However, due to significant procedural limitations and technical complexities of HBP associated with the risk of causing distal conduction block, high capture threshold, and low sensed R wave amplitude (Fig. 1), researchers and clinicians have faced the necessity to develop a better pacing modality for delivering physiological pacing, the LBAP therapy [13]. After that, the advantages of the LBAP technique in patients with cardiomyopathy have been demonstrated across several studies [14].

Mechanisms for LBBB reversal with His bundle pacing

His bundle pacing (HBP) has arisen as a novel and alternative method for cardiac resynchronization therapy (CRT) in patients with heart failure (HF) and left bundle branch block (LBBB). The main reason for implementing effective ventricular resynchronization and more physiological activation is the obvious improvement in cardiac function. This method can also significantly reduce QRS duration and restore normal intrinsic activation patterns in patients with ventricular conduction delays, as demonstrated by Ali et al. [21].

Thus, for the first time, the concept of longitudinal dissociation with the fibers within the His bundle committed to the left bundle with asynchronous conduction resulting in an LBBB pattern was described. The study showed that localized lesions within the His bundle induced LBBB. Meanwhile, stimulation of the HB proximal to the intra-His lesion could lead to ventricular depolarization. HB stimulation at a site distal to the lesion, in turn, resulted in narrow QRS complexes due to synchronous impulse conduction to LBB and RBB. These fundamental concepts confirmed the feasibility of HBP, including in advanced His to ventricular electrogram interval (HV) disease stages [6].

In some cases, the factors like the higher lead revision rate or pacing thresholds can prevent HBP from reversing LBB. Concerning the mechanisms for HBP narrowing or reversing BBB, there are the following:

- The pacing lead is placed distal to the site of BBB fibers within the HB are ordered in strands predestined for the LBB or RBB. The position of a pacing lead can reverse conduction delays within the HB [25].

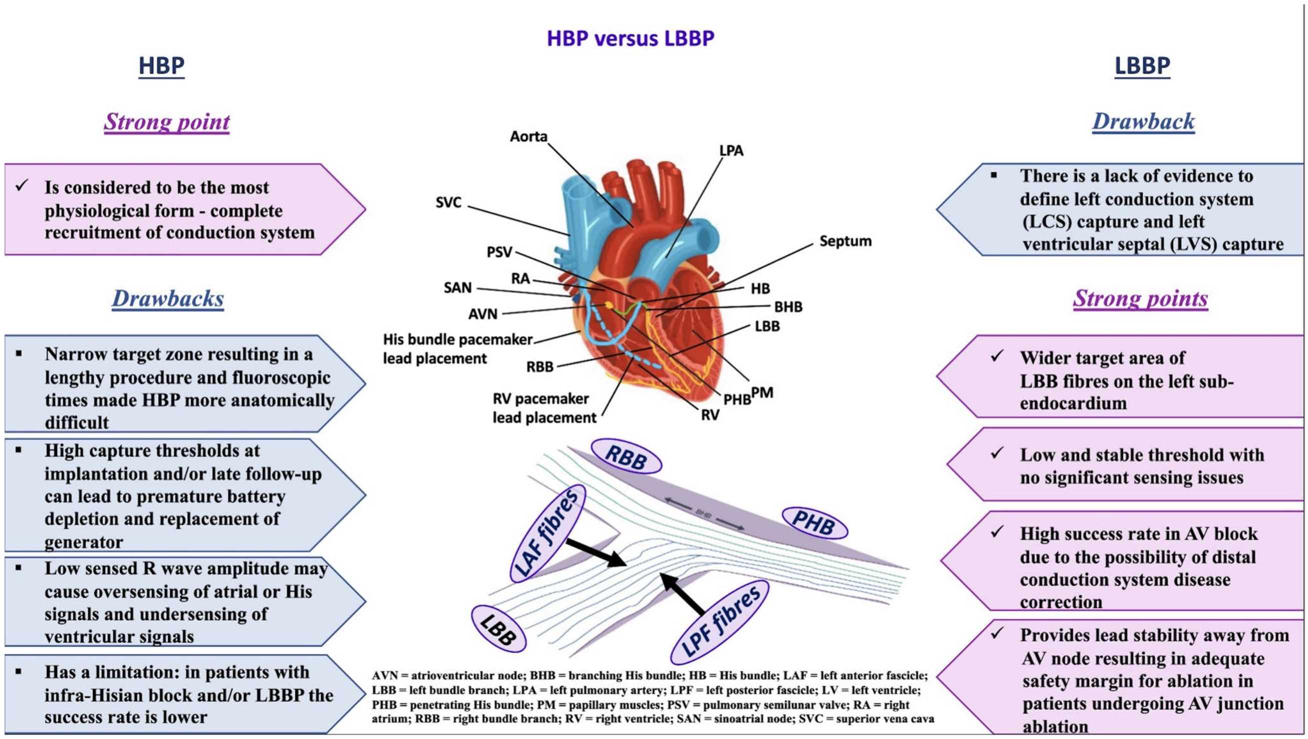

Fig. 1 Advantages and disadvantage of His bundle pacing (HBP) vs left bundle branch pacing (LBBP)

- The connection between source and sink: the block is overcome with sufficient stimulus for activation of distal dormant tissue based on the source-sink connection during pacing versus intrinsic impulse propagation [25].
- Retrograde activation: the activation of the His-Purkinje system happens through the capture of an upper septal branch that permits onward antegrade activation beyond a block site [25].

Acute and chronic effects of HBP and LBBP

In a prospective crossover study, Catanzariti et al. proved that during direct HBP, physiologic distribution of myocardial blood flow was preserved more in comparison with right ventricular apical pacing [26]. In another crossover trial, the evaluation of myocardial perfusion and mitral regurgitation showed significant improvement in the assessed indicators. Still, HBP, in this case, had no effect on LV systolic function [27]. The results of the study by Zanon et al., meanwhile, demonstrated that HBP mode in comparison with RV apical pacing in patients undergoing permanent implantation of a HBP lead contributed to improvement in LV systolic function and echocardiographic indices of ventricular synchrony [12].

In a more recent study, where the effects of HBP in patients with LV systolic dysfunction, first-degree atrioventricular block (AVB), and either RBBB or narrow QRS complex were evaluated, it was proved that temporary HBP did not lead to an increase in QRS duration (in comparison with temporary biventricular pacing) [28]. A randomized study by Ellenbogen and Huizar demonstrated that LVEF was significantly higher after 12 months of His pacing in patients compared with AVB, narrow QRS, and LVEF > 0.40 as compared with RVP [29]. Evaluating the long-term lead performance of His pacing, Chen et al. reported successful HBP in 80% of cases with markedly lower death or HF hospitalization in HBP compared to RVP patients at five years of follow-up [30].

HBP and LBBP in CRT-eligible populations

Several prospective randomized studies proved the effects of BVP in reducing mortality rates and heart failure hospitalization, improving quality of life, and increased exercise capacity. However, the CRT non-response is up to 30% in all CRT candidates [31]. In patients with narrow QRS or moderate QRS prolongation (i.e., < 130 ms), BVP can cause prolongation of ventricular activation time and worsen dyssynchronous activation [32]. Furthermore, right ventricular pacing should not be applied to patients with impaired LVEF to avoid the development of pacing-induced cardiomyopathy. Since BVP does not deliver true physiological pacing, it has not demonstrated superiority over RVP in patients with LVEF > 45%, according to the results of the BIOPACE trial [33].

A multicenter study by Ali et al. evaluated the feasibility and outcomes of the LBBAP method in CRT-eligible patients or those who underwent unsuccessful CRT. In this cohort study, all patients had NYHA class II to IV, baseline LVEF ≤ 50%, and indications for ventricular pacing and/or CRT. Based on the results, LBBAP was associated with reduced paced QRS duration, improving clinical and echocardiographic outcomes. Hence, LBBAP can be a feasible, safe, and potentially an alternative option for CRT [21]; however, this option needs to be tested in large clinical trials.

In a randomized crossover study, Gasparini et al. demonstrated no significant difference in clinical and echocardiographic improvements while applying HBP compared with BVP [34]. However, certain disadvantages of HBP, such as higher pacing thresholds and the inability to correct distal LBBB, were a limitation for using this technique, as demonstrated by Leclercq et al. comparing HBP with BVP [35].

Clinical perspectives of His bundle pacing and left bundle branch pacing area in heart failure

Cardiac resynchronization therapy is the gold standard in the management of patients with systolic heart failure and electromechanical dyssynchrony, as evidenced by a wide QRS duration. For over two decades, the resynchronization method has been through by ventricular pacing. We have strong data using prospective randomized studies that show biventricular pacing improves quality of life New York Heart Association classification, left ventricular ejection fraction, and left ventricular volumes. However, despite strong clinical evidence regarding the efficacy of biventricular pacing, it is estimated that approximately 1/3 of patients have no clinical benefit or response to CRT via LV lead placement (Table 1).

HBP

Conduction system pacing, either via His bundle pacing or more recently left bundle branch pacing, has emerged as a viable alternative to traditional left ventricular CRT in patients with congestive heart failure. His bundle pacing via activation of the His-Purkinje conduction system and resultant physiologic ventricular activation has been promoted as a favorable alternative to Bi ventricular pacing strategy in patients with and without heart failure (Fig. 2).

LBBAP

Left bundle branch area pacing has been suggested as an effective alternative to overcome the limitations of His bundle pacing. Left bundle branch pacing allows for physiologic stimulation of the left bundle component of cardiac conduction system like HBP, however, with improved leads to stability and fewer implant and post-op technologic challenges. Left bundle branch pacing has a larger target area and somewhat fewer technological implant challenges. Lead stability and thresholds also appear to be improved compared to His

Table 1 Current limitations of HBP and LBBP in heart failure

HBP	LBBAP
1. Higher pacing thresholds	1. Learning curve regarding the use of the delivery systems of several vendors
2. Increased implantation time and fluoroscopy time	2. Learning curve regarding the left bundle branch area pacing site and placement of the lead deep into septal
3. Lead dislodgement	3. Risk of deep septal lead placement, including but not limited to perforation into the left ventricle
4. Elevated pacing thresholds at follow-up	4. Potential for higher complication rate should the deep intra-septal lead need to be extracted in the future
5. Rapid battery depletion due to an increase in pacing thresholds	5. Absence of big randomized controlled data comparing left bundle branch area pacing in patients requiring CRT in comparison to traditional biventricular pacing
6. Failure to achieve His bundle capture	6. Accurate understanding of criteria for left bundle branch area capture by implanting physician
7. Absence of a unique CPT code resulting in no increase in payment despite increased physician time utilization, EP lab utilization, and use of additional sheaths and equipment	7. Long-term (> 12 months) lead performance with deep septal implantation of pacing lead
8. Lack of large RCT data regarding outcomes in comparison to traditional CRT	8. Increased procedure time and fluoroscopy time, in the initial implant learning curve
9. Nuanced implant technique, limited to mostly electrophysiologists	9. No unique CPT code; hence, no payment for increased physician procedure time and EP lab time utilization
10. Not scalable	10. Equipment issues: new lead design and delivery systems are being designed
11. High reintervention rate	
12. Concerns regarding aortic valve endocarditis if lead related infection	

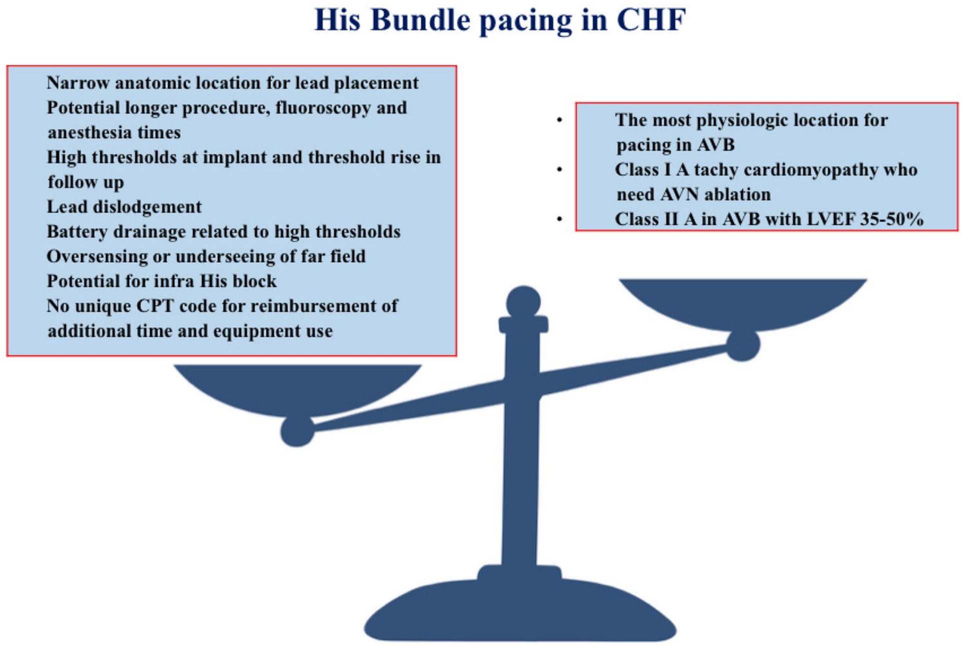

Fig. 2 His bundle pacing in CHF

bundle pacing. Nonetheless, it is important to understand anatomy and fluoroscopic views when implantation of the lead to achieve accurate left bundle capture.

Vijayaraman et al. recently published their data regarding the feasibility and outcomes of left bundle branch area pacing for CRT in a multicenter international collaborative study. LBBP was attempted in 325 patients with LVEF < 50% and an indication for CRT. CRT was successfully achieved in 277 of these patients (85%). QRS configuration at baseline was left bundle branch block in 39%, and non-left bundle branch block in 46%. Procedure times were 105 ± 54 min, and fluoroscopy time was acceptable at 19 ± 15 min. Importantly, left bundle branch area pacing thresholds were 0.6 ± 0.3 V @0.5 ms, and R wave amplitude was acceptable at 10.6 ± 6 mV at implantation. Sensing and thresholds remain stable during the follow-up of approximately 6 months. The importantly clinical and echocardiographic response was observed in 72 to 73% of the patients who achieved left bundle branch pacing. This study proved that left bundle branch pacing is a feasible alternative for cardiac resynchronization therapy providing acceptable pacing and sensing parameters both in the short and long term with no excessive procedure times and successful clinical outcomes.

Recent randomized LBBP-RESYNC study (40 pts) showed that patient randomized to LBBP has higher LVEF improvement. In this study, 10% LBBP patients were crossover to biventricular CRT and 20% of biventricular CRT were crossover to LBBB pacing due to the problems with lead placement. Which on the one hand showed that is not always possible to perform both of techniques in one patient but in case of the impossibility of one of the methods it is possible to change to another. Both HBP and LBAP could be helpful also in patients without HF in whom we expect a high rate of RV stimulation. HBP is the most physiological pacing modality that restores normal ventricular activation and has been demonstrated to achieve greater hemodynamic response over BVP in patients [44]. Confirmation of LBB capture is essential to distinguish LBBP from LVSP, as LBBP ensures rapid LV activation propagation via conduction system rather than myocardial endocardium and hence improves ventricular electrical synchrony.

Pacing strategies for HF and AF patients

Atrial fibrillation (AF), the most common arrhythmia, increases the risk of death and hospitalization in 76% of HF patients, and the structural and neurohormonal changes in HF make, in turn, the development and progression of AF much more likely [15]. AF ablation was associated with a significant improvement in LVEF, independent of the severity of left ventricular dysfunction [16].

In a study, Molhoek et al. patients with AF showed a milder degree of response to CRT compared to those with sinus rhythm. However, the long-term survival rate was comparable among these two groups of patients [36, 37]. According to the guidelines, CRT should be performed in patients with HF and LVEF ≤ 35% with NYHA class III or IV if they are in AF and have intrinsic QRS ≥ 130 ms, provided a strategy to ensure biventricular capture is in place. Meanwhile, AV junction ablation should be added in the case of incomplete biventricular pacing (< 90–95%) due to conducted AF [38].

An intrinsic and irregular spontaneous AF rhythm reduces the percentage of effectively biventricular paced captured beats, making CRT delivery more challenging in those patients with AF [39]. Nevertheless, the deleterious hemodynamic effects of irregular, spontaneous rhythm could be eliminated by AVJ ablation delivery. Hence, in the context of CRT in patients with HF and concomitant AF, many studies have shown AVJ ablation's benefits for optimization of CRT procedure [40]. The MUSTIC AF trial is considered the first randomized trial showing potential benefits of CRT in HF patients with permanent AF by determining biventricular stimulation as a preferred mode compared to RV [41]. An observational study by Gasparini et al. demonstrated that significant improvements in LVEF, the left ventricular end-systolic volume (LVESV), and exercise capacity were observed in AF patients who underwent AVJ ablation [37, 38]. Deshmukh et al. demonstrated further improvement in LV dimensions with His pacing in patients with impaired LV systolic function and AF prior to AV node ablation and achieved procedural success in 60% of cases [36, 37].

On the other side, in selected patients with AF and HF, especially with uncontrolled heart rate, the "ablate-and-pace" strategy can be beneficial, resulting in improvement of LVEF and the NYHA functional class [17]. However, potential downsides of such a strategy are the risk of progressive left ventricular dyssynchrony, deterioration of LVEF, and the risk of sudden death after AV node ablation [18]. To prevent mechanical ventricular dyssynchrony and further HF aggravation, cardiac resynchronization therapy (CRT) is an effective option, although patients with AF show a milder degree of improvement with CRT compared with patients with sinus rhythm [19].

In patients with HF and sinus rhythm, PR prolongation is a prospective issue for pacing. A PR $\geq$ 200 ms is significantly associated with 58% higher mortality in the long term regardless of QRS duration [20]. According to the results of the studies, the prevalence of prolonged PR in patients with HF and CRT stands at 18–52% [21].

The benefits of HBP in HF can potentially apply to patients with narrow QRS and PR prolongation by providing AV synchrony without inducing ventricular dyssynchrony [22]. The EuroHeart Failure survey identified that about 75% of patients hospitalized with a suspected diagnosis of HF had normal QRS duration ($\leq$ 120 ms) [23]. Meanwhile, up to 50% of HF patients with a narrow QRS complex show echocardiographic evidence of ventricular dyssynchrony and hence might benefit from CRT, resulting in frequent off-label use of CRT [24]. Noteworthy, HBP has a higher success rate in patients with symptomatic AV block if the level is nodal compared to infranodal [4]. Anatomy of the mechanism of pacing procedures should be considered during maneuvers to ensure that the lead is positioned distal to the site of diseased HB [4].

At present with the development of dedicated tools for direct HBP, the success rate of implantations has become more than 90%. Moreover, in most cases, the acceptable pacing thresholds can be achieved [37]. Su et al. evaluated the long-term performance of HBP following AV node ablation in patients with AF and HF. It was demonstrated that HBP combined with AV node ablation was effective in AF patients with drug-refectory HF. Furthermore, high pulmonary artery systolic pressure (PASP), elevated serum creatinine (Scr), and low LVEF at baseline were established as independent predictors of the composite endpoint of all-cause mortality or HF hospitalization [38].

The study by Vinther et al. observed HF patients with LBBB, demonstrated that His-CRT provided similar clinical improvement in comparison with BiV-CRT at the expense of higher pacing thresholds [39]. One more study successfully achieved permanent HBP in 80% of patients with AF, with narrow QRS duration, both HF with a preserved ejection fraction (HFpEF) and HF with reduced ejection fraction (HFrEF). The results of the study demonstrated a reduction in hospital admissions as well as an improvement in cardiac function [40].

Physiological pacing in patients with heart failure with preserved ejection fraction

Increase heart rate (HR) may have the potential to reduce the risk for heart failure hospitalization, atrial fibrillation (AF), and cerebrovascular stroke as these outcomes are increased in patients with a normal or preserved ejection fraction on HR-lowering treatments. Therefore, lower HR elevation employing physiological conduction system pacing in patients with HFpEF will decrease left atrial and left ventricular filling pressures. There is an ongoing randomized trial that is investigating whether pacing with a higher heart rate is beneficial for patients with HFpEF and pacemakers with intrinsic AV conduction or CRT. Also, physiological pacing (CRT or His) could be beneficial in patients with HF, LVEF 35–50%, and indications for pacemaker implantation with high expected percent of pacing (BLOCK HF study) [42]. Again, physiologic accelerated pacing as a treatment in patients with heart failure with preserved ejection fraction (PACE HFpEF) trial is now under investigation hypothesizes that a personalized lower HR elevation employing physiological conduction system pacing in patients with HFpEF will decrease left atrial and left ventricular filling pressure [43].

Conclusion

Implementing physiological pacing techniques directly activating the conduction system has been and continues to be a crucial issue in managing cardiac conduction disease. HBP is the most physiological pacing modality that restores normal ventricular activation and has been demonstrated to achieve greater hemodynamic response over BVP in patients. HBP combined with AV node ablation showed effectiveness in AF patients with drug-refectory HF. Left bundle branch area pacing has been suggested as an effective alternative to overcome the limitations of His bundle pacing. But, left bundle branch pacing and His bundle pacing have a larger target area and somewhat fewer technological implant challenges. In fact, future studies and large-scale clinical trials are expected to validate HBP and LBBP's safety, reliability, and long-term performance for physiological pacing in several groups of patients.

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Availability of data and materials No dataset generated.

Declarations

Ethical approval No ethical approval needed.

Competing interests The authors declare no competing interests.

References

1. Kawashima T, Sasaki H (2005) A macroscopic anatomical investigation of atrioventricular bundle locational variation relative to the membranous part of the ventricular septum in elderly human hearts. Surg Radiol Anat 27(3):206–213. https://doi.org/10.1007/s00276-004-0302-7
2. Arora V, Suri P (2021) Physiological pacing: a new road to future. Indian J Clin Cardiol 2(1):32–43. https://doi.org/10.1177/2632463620978045
3. Vijayaraman P, Dandamudi G (2016) Anatomical approach to permanent His bundle pacing: optimizing His bundle capture. J Electrocardiol 49(5):649–57.https://doi.org/10.1016/j.jelectrocard.2016.07.003
4. Ponnusamy SS (2021) A road to physiological pacing. Indian J Clin Cardiol 2(1):7–9. https://doi.org/10.1177/26324636211001585
5. Padala SK, Master VM, Terricabras M, Chiocchini A, Garg A, Kron J, Shepard R et al (2020) Initial experience, safety, and feasibility of left bundle branch area pacing: a multicenter prospective study. JACC Clin Electrophysiol 6(14):1773–1782. https://doi.org/10.1016/j.jacep.2020.07.004
6. Zanon F, Bacchiega E, Rampin L, Aggio S, Baracca E, Pastore G, Marotta T et al (2008) Direct His bundle pacing preserves coronary perfusion compared with right ventricular apical pacing: a prospective, cross-over mid-term study. Europace 10(5):580–587. https://doi.org/10.1093/europace/eun089
7. Narula OS, Scherlag BJ, Samet P (1970) Pervenous pacing of the specialized conducting system in man. His bundle and A-V nodal stimulation. Circulation 41(1):77–87.https://doi.org/10.1161/01.cir.41.1.77
8. Lustgarten DL, Crespo EM, Arkhipova-Jenkins I, Lobel R, Winget J, Koehler J, Liberman E et al (2015) His-bundle pacing versus biventricular pacing in cardiac resynchronization therapy patients: a crossover design comparison. Heart Rhythm 12(7):1548–1557. https://doi.org/10.1016/j.hrthm.2015.03.048
9. Sharma PS, Dandamudi G, Herweg B, Wilson D, Singh R, Naperkowski A, Koneru JN et al (2018) Permanent His-bundle pacing as an alternative to biventricular pacing for cardiac resynchronization therapy: a multicenter experience. Heart Rhythm 15(3):413–420. https://doi.org/10.1016/j.hrthm.2017.10.014
10. Occhetta E, Bortnik M, Marino P (2007) Permanent parahisian pacing. Indian Pacing Electrophysiol J 7(2):110–125
11. Kronborg MB, Mortensen PT, Gerdes JC, Jensen HK, Nielsen JC (2011) His and para-His pacing in AV block: feasibility and electrocardiographic findings. J Interv Card Electrophysiol 31(3):255–262. https://doi.org/10.1007/s10840-011-9565-1
12. Zanon F, Ellenbogen KA, Dandamudi G, Sharma PS, Huang W, Lustgarten DL, Tung R et al (2018) Permanent His-bundle pacing: a systematic literature review and meta-analysis. Europace 20(11):1819–1826. https://doi.org/10.1093/europace/euy058
13. Huang W, Su L, Wu S, Xu L, Xiao F, Zhou X, Ellenbogen KA (2017) A novel pacing strategy with low and stable output: pacing the left bundle branch immediately beyond the conduction block. Can J Cardiol 33(12):1736.e1-1736.e3. https://doi.org/10.1016/j.cjca.2017.09.013
14. Wu S, Su L, Vijayaraman P, Zheng R, Cai M, Xu L, Shi R et al (2021) Left bundle branch pacing for cardiac resynchronization therapy: nonrandomized on-treatment comparison with His bundle pacing and biventricular pacing. Can J Cardiol 37(2):319–328. https://doi.org/10.1016/j.cjca.2020.04.037
15. Kotecha D, Piccini JP (2015) Atrial fibrillation in heart failure: what should we do? Eur Heart J 36(46):3250–3257. https://doi.org/10.1093/eurheartj/ehv513
16. Gentlesk PJ, Sauer WH, Gerstenfeld EP, Lin D, Dixit S, Zado E, Callans D et al (2007) Reversal of left ventricular dysfunction following ablation of atrial fibrillation. J Cardiovasc Electrophysiol 18(1):9–14. https://doi.org/10.1111/j.1540-8167.2006.00653.x
17. Manolis AG, Katsivas AG, Lazaris EE, Vassilopoulos CV, Louvros NE (1998) Ventricular performance and quality of life in patients who underwent radiofrequency AV junction ablation and permanent pacemaker implantation due to medically refractory atrial tachyarrhythmias. J Interv Card Electrophysiol 2(1):71–76. https://doi.org/10.1023/a:1009721008761
18. O'Keefe JH Jr, Abuissa H, Jones PG, Thompson RC, Bateman TM, McGhie AI, Ramza BM et al (2005) Effect of chronic right ventricular apical pacing on left ventricular function. Am J Cardiol 95(6):771–773. https://doi.org/10.1016/j.amjcard.2004.11.034
19. Molhoek SG, Bax JJ, Bleeker GB, Boersma E, van Erven L, Steendijk P, van der Wall EE et al (2004) Comparison of response to cardiac resynchronization therapy in patients with sinus rhythm versus chronic atrial fibrillation. Am J Cardiol 94(12):1506–1509. https://doi.org/10.1016/j.amjcard.2004.08.028
20. Olshansky B, Day JD, Sullivan RM, Yong P, Galle E, Steinberg JS (2012) Does cardiac resynchronization therapy provide unrecognized benefit in patients with prolonged PR intervals? The impact of restoring atrioventricular synchrony: an analysis from the COMPANION Trial. Heart Rhythm 9(1):34–39. https://doi.org/10.1016/j.hrthm.2011.07.038
21. Ali N, Keene D, Arnold A, Shun-Shin M, Whinnett ZI, Afzal Sohaib SM (2018) His bundle pacing: a new frontier in the treatment of heart failure. Arrhythm Electrophysiol Rev 7(2):103–110. https://doi.org/10.15420/aer.2018.6.2
22. Ruschitzka F, Abraham WT, Singh JP, Bax JJ, Borer JS, Brugada J, Dickstein K et al (2013) EchoCRT Study Group.

Cardiac-resynchronization therapy in heart failure with a narrow QRS complex. N Engl J Med 369(15):1395–405.https://doi.org/10.1056/NEJMoa1306687
23. Narula OS (1977) Longitudinal dissociation in the His bundle. Bundle branch block due to asynchronous conduction within the His bundle in man. Circulation 56:996–1006
24. Vijayaraman P, Chung MK, Dandamudi G, Upadhyay GA, Krishnan K, Crossley G, Bova Campbell K, Lee BK, Refaat MM, Saksena S, Fisher JD, Lakkireddy D (2018) ACC's Electrophysiology Council. His bundle pacing. J Am Coll Cardiol 72(8):927–947
25. Sohaib SA, Wright I, Lim E, Moore P, Lim PB, Koawing M, Lefroy DC et al (2015) Atrioventricular optimized direct His bundle pacing improves acute hemodynamic function in patients with heart failure and PR interval prolongation without left bundle branch block. JACC Clin Electrophysiol 1:582–591
26. Catanzariti D, Maines M, Cemin C, Broso G, Marotta T, Vergara G (2006) Permanent direct His bundle pacing does not induce ventricular dyssynchrony unlike conventional right ventricular apical pacing. J Interv Card Electrophysiol 16:81–92
27. Kronborg MB, Mortensen PT, Poulsen SH, Gerdes JC, Jensen HK, Nielsen JC (2014) His or para-His pacing preserves left ventricular function in atrioventricular block: a double-blind, randomized, crossover study. Europace 16(8):1189–1196. https://doi.org/10.1093/europace/euu011
28. Dandamudi G et al (2018) Permanent His-bundle pacing: long-term lead performance and clinical outcomes. Heart Rhythm 15(5):696–702. https://doi.org/10.1016/j.hrthm.2017.12.022
29. Ellenbogen KA, Huizar JF (2012) Foreseeing super-response to cardiac resynchronization therapy: a perspective for clinicians. J Am Coll Cardiol 59:2374–7
30. Chen X, Ye Y, Wang Z, Jin Q, Qiu Z, Wang J, Qin S et al (2022) Cardiac resynchronization therapy via left bundle branch pacing vs. optimized biventricular pacing with adaptive algorithm in heart failure with left bundle branch block: a prospective, multi-centre, observational study. Europace 24(5):807–816.https://doi.org/10.1093/europace/euab249
31. Molhoek SG, Bax JJ, Bleeker GB, Boersma E, van Erven L, Steendijk P, van der Wall EE, Schalij MJ (2004) Comparison of response to cardiac resynchronization therapy in patients with sinus rhythm versus chronic atrial fibrillation. Am J Cardiol 94: 1506–1509
32. Glikson M, Nielsen JC, Kronborg MB, Michowitz Y, Auricchio A, Barbash IM, Barrabés JA (2022) 2021 ESC guidelines on cardiac pacing and cardiac resynchronization therapy: developed by the task force on cardiac pacing and cardiac resynchronization therapy of the European Society of Cardiology (ESC): with the special contribution of the European Heart Rhythm Association (EHRA). Europace 24(4):699. https://doi.org/10.1093/europace/euac023)
33. Gasparini M, Regoli F, Galimberti P, Ceriotti C, Cappelleri A (2009) Cardiac resynchronization therapy in heart failure patients with atrial fibrillation. Europace 11(Suppl 5):v82–6. https://doi.org/10.1093/europace/eup273
34. Gasparini M, Regoli F, Galimberti P, Ceriotti C, Cappelleri A (2009) Cardiac resynchronization therapy in heart failure patients with atrial fibrillation. Europace 11(Suppl 5):v82–6.https://doi.org/10.1093/europace/eup273
35. Leclercq C, Walker S, Linde C, Clementy J, Marshall AJ, Ritter P et al (2002) Comparative effects of permanent biventricular and right-univentricular pacing in heart failure patients with chronic atrial fibrillation. Eur Heart J 23:1780–7
36. Deshmukh R, Casavant DA, Romanyshyn M, Anderson K (2000) Permanent, direct His-bundle pacing: a novel approach to cardiac pacing in patients with normal His-Rurkinje activation. Circulation 101:869–877. https://doi.org/10.1161/01.CIR.10L8.869)
37. Ciesielski A, Boczar K, Siekiera M, Gajek J, Sławuta A (2022) The clinical utility of direct His-bundle pacing in patients with heart failure and permanent atrial fibrillation. Acta Cardiol 77(2):114–121. https://doi.org/10.1080/00015385.2021.1901021)
38. Su L, Cai M, Wu S, Wang S, Xu T, Vijayaraman P, Huang W (2020) Long-term performance and risk factors analysis after permanent His-bundle pacing and atrioventricular node ablation in patients with atrial fibrillation and heart failure. Europace 22(Suppl_2):ii19-ii26.https://doi.org/10.1093/europace/euaa306
39. Vinther M, Risum N, Svendsen JH, Møgelvang R, Philbert BT (2021) A randomized trial of His pacing versus biventricular pacing in symptomatic HF patients with left bundle branch block (His-alternative). JACC Clin Electrophysiol 7(11):1422–1432. https://doi.org/10.1016/j.jacep.2021.04.003)
40. Huang W, Su L, Wu S et al (2017) Benefits of permanent His bundle pacing combined with atrioventricular node ablation in atrial fibrillation patients with heart failure with both preserved and reduced left ventricular ejection fraction. J Am Heart Assoc 6:e005309.https://doi.org/10.1161/JAHA.116.005309
41. Infeld M, Wahlberg K, Cicero J et al (2021) Personalized pacing for diastolic dysfunction and heart failure with preserved ejection fraction: design and rationale for the *my*PACE randomized controlled trial. Heart Rhythm O2 3(1):109–116. Published 2021 Dec 7. https://doi.org/10.1016/j.hroo.2021.11.015
42. Curtis AB, Worley SJ, Adamson PB et al (2013) Biventricular pacing for atrioventricular block and systolic dysfunction. N Engl J Med 368(17):1585–1593. https://doi.org/10.1056/NEJMoa1210356
43. Daniel L Lustgarten, Physiologic Accelerated Pacing as a Treatment in Patients With Heart Failure With Preserved Ejection Fraction (PACE HFpEF), ClinicalTrials.gov Identifier: NCT04546555. https://clinicaltrials.gov/ct2/show/NCT04546555
44. Kusumoto FM, Schoenfeld MH, Barrett C et al (2019)2018 ACC/AHA/HRS guideline on the evaluation and management of patients with bradycardia and cardiac conduction delay: executive summary: a report of the American College of Cardiology/American Heart Association Task Force on Clinical Practice Guidelines, and the Heart Rhythm Society. J Am Coll Cardiol 74(7):932–987. https://doi.org/10.1016/j.jacc.2018.10.043

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