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Conduction System Pacing Leads: Lumenless versus Stylet-driven Technologies in Contemporary Practice

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Abstract

Conduction system pacing (CSP), including His bundle pacing and left bundle branch area pacing (LBBAP), has emerged as a physiological alternative to right ventricular pacing and an evolving modality for cardiac resynchronisation therapy. As clinical adoption expands, lead technology has become central to procedural success, electrical performance, and long-term safety. Historically, CSP has relied on lumenless leads (LLL), while stylet-driven leads (SDL) are increasingly used, particularly for LBBAP. Current evidence indicates that CSP procedures are feasible, reproducible, and show positive trends in outcomes for both bradycardia and heart failure patients, with both LLL and SDL achieving high implant success and comparable pacing parameters. However, differences in mechanical design may influence implantation technique, complication profiles, and long-term durability. Although observational studies and registries support the safety and effectiveness of both lead types, long-term data on lead fracture, extractability, and device-specific performance remain limited. At present, no clear superiority of one platform over the other can be established. Lead selection should therefore be individualised, guided by anatomy, operator experience and device-specific evidence, while further prospective studies are needed to optimise CSP lead design and long-term outcomes.

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Cardiac pacing is an established therapy for bradyarrhythmias, but its long-term effects on ventricular activation and cardiac function are increasingly recognised.[1] Conventional right ventricular pacing (RVP) produces non-physiological electrical activation that can result in ventricular dyssynchrony, left ventricular (LV) dysfunction, and pacemaker-induced cardiomyopathy.[2] These limitations have stimulated the development of pacing strategies that better preserve normal ventricular activation.[3]

Conduction system pacing (CSP), including His bundle pacing (HBP) and left bundle branch area pacing (LBBAP), directly engages the native His–Purkinje system and provides a more physiological pattern of ventricular activation.[4] CSP is increasingly used as an alternative to RVP in patients with atrioventricular block and high anticipated pacing burden, and is also emerging as a novel approach to deliver cardiac resynchronisation therapy (CRT) in selected heart failure patients, particularly those with left bundle branch block.[5] Early evidence suggests CSP may improve electrical synchrony and promote reverse remodelling compared with conventional pacing strategies.[3] CSP procedures show high feasibility and reproducibility, supported by tools like helix locking mechanisms, multiple sheaths, and stylet-driven leads that simplify the workflow and improve procedural efficiency. Unlike traditional pacing, CSP often requires deep septal lead implantation and strict electrocardiographic confirmation of conduction system capture. Therefore, lead design plays a central role in procedural feasibility, electrical performance and long-term safety.

This review summarises the role of CSP in bradycardia and heart failure indications, with a specific focus on lead technology for LBBAP. I compare the mechanical and clinical characteristics of LLL and SDL platforms, review available performance and safety data, and discuss future directions in the development of dedicated CSP lead systems.

Conduction System Pacing Instead of Right Ventricular Pacing

In patients with atrioventricular (AV) block who are expected to require a high burden of ventricular pacing, CSP is increasingly recognised as a more physiological alternative to RVP.[1] By directly engaging the His–Purkinje system, both HBP and LBBAP can preserve or restore near-normal ventricular activation, thereby reducing electrical dyssynchrony and the risk of pacemaker induced cardiomyopathy.[2] This is particularly relevant because the vast majority of AV block occurs at the nodal or intra-Hisian level, where conduction can often be effectively recruited with CSP. LBBAP is generally favoured in infra-nodal block due to higher implant success rates, more stable electrical parameters, and fewer lead revisions compared with HBP.[7] In patients with preserved or mildly reduced left ventricular ejection fraction (LVEF), CSP may be considered as an alternative to RVP when a substantial pacing burden is anticipated. In those with reduced LVEF (≤40%) and an indication for pacing, biventricular cardiac resynchronisation therapy (BiV-CRT) remains guideline-endorsed.[6,8]

However, CSP-CRT is emerging as a reasonable alternative, particularly when coronary sinus lead implantation is challenging or when a more physiological activation pattern is desired. Since publication of the EHRA consensus statement, additional data have emerged.[6] Recently, MELOS RELOADED, a multicentre European registry-based study, evaluated pacemaker patients with AV block, LVEF >40%, and >20% ventricular pacing.[9] The primary endpoint was all-cause mortality derived from

national registries. After 1:1 propensity score matching between RVP and LBBAP patients, 3,382 matched individuals were analysed. At 4-year follow-up, the analysis demonstrated an absolute survival difference of 11.8% in favour of LBBAP (P < .001). LBBAP was a strong independent predictor of reduced mortality (HR 0.53; 95% CI [0.42–0.65]; p<0.001). Within the LBBAP cohort, lack of confirmed left bundle branch capture, a lower percentage of ventricular pacing, and advanced age were independently associated with increased mortality. These findings underscore the positive trends in outcomes for bradycardia patients with CSP, showing superior survival benefits over RVP in reproducible multicentre settings.

Despite these encouraging findings, randomised data specifically focused on AV block in patients with reduced LVEF remain limited, and ongoing trials are expected to better define the relative roles of CSP and BiV pacing in this population.

CSP for Heart Failure without a Bradycardia Pacing Indication

In heart failure patients, particularly those with reduced LVEF and left bundle branch block, CRT is traditionally delivered via BiVP.[1] However, BiVP is limited by anatomical challenges, non-response rates of approximately one-third and suboptimal electrical resynchronisation in certain conduction patterns.[5,10] CSP has emerged as a promising alternative method of delivering CRT by restoring more physiological ventricular activation. HBP can correct LBBB in selected patients and has shown comparable short-term clinical and echocardiographic responses to BiVP in small trials.[5,8] However, broader adoption is limited by higher pacing thresholds, potential lead instability, and difficulty correcting distal conduction disease.

LBBAP, by pacing more distally within the conduction system, offers higher implant success rates, stable pacing thresholds, and effective QRS narrowing. Observational studies and several small randomised trials suggest that CSP-CRT – particularly with LBBAP – can achieve similar or greater improvements in LVEF, functional status, and reverse remodelling compared with BiV-CRT, with comparable short-term clinical outcomes.[5,8] Therefore, CSP is increasingly used as a primary CRT strategy, a bailout option when coronary sinus lead placement fails, or as an upgrade in CRT non-responders. Nevertheless, long-term outcome data and larger randomised trials are still required before CSP can fully replace conventional BiV-CRT in all eligible heart failure patients without a standard pacing indication. CSP in heart failure demonstrates feasible and reproducible procedures with positive trends in outcomes, such as improved LVEF and reduced hospitalisations, supported by tools that simplify implantation workflows.

Lead Technology in LBBAP

Beyond pacing strategy selection, this review also addresses the clinically relevant issue of lead design in LBBAP, specifically comparing lumenless leads (LLL) and stylet-driven leads (SDL).[11] Unlike conventional pacing, CSP requires precise engagement of the specialised conduction system, often involving deep septal lead deployment and strict electrocardiographic and electrical criteria for capture. Consequently, lead design – including diameter, stiffness, helix configuration, torque transmission, and compatibility with delivery systems – plays a critical role in procedural feasibility, safety, and long-term performance. Historically, CSP, particularly HBP, has predominantly relied on lumenless leads, such as the Medtronic 3830.[6] These leads have a small diameter, fixed helix and no inner lumen, allowing a low-profile design and excellent torque transmission through the lead body. They are typically delivered via dedicated sheaths and have demonstrated reliable performance, particularly in HBP.[11]

More recently, technological advances and dedicated delivery systems have facilitated increasing use of stylet-driven leads for LBBAP. SDLs have a larger diameter and an extendable–retractable helix. The presence of a stylet provides greater shaft support and directional control, which may facilitate septal penetration and allow continuous pacing assessment during lead advancement – a key procedural advantage in LBBAP.[12] The structural and mechanical differences between LLL and SDL may influence implantation technique, pacing performance and complication profiles. SDLs offer greater stiffness and support, potentially simplifying deep septal lead placement. In contrast, LLLs have a smaller profile and fixed helix design, which may be associated with favourable long-term durability.[11,12]

A recent systematic review and meta-analysis comparing the two lead types demonstrated that implant success rates and electrical pacing parameters are largely comparable between LLL and SDL.[11] However, a higher rate of lead-related complications was observed with SDL, likely reflecting differences in implantation technique, lead mechanics, and operator experience rather than intrinsic inferiority of the lead design. Importantly, current evidence remains insufficient to determine whether meaningful differences exist in long-term lead performance or extractability. Lead-related complications in CSP differ from those seen with conventional pacing due to deep septal positioning. Reported issues include septal perforation into the left ventricular cavity, lead dislodgement, rising capture thresholds, helix damage and rare cases of interventricular septal haematoma.

Long-term mechanical stress on leads embedded within the septum raises additional concerns regarding potential conductor fracture, although robust long-term data are lacking. Whether lead design influences these risks remains uncertain. Similarly, more data on the long-term extractability of CSP leads with both LLLs and SDLs are needed. Deep septal lead positioning may result in fibrotic encapsulation, potentially increasing the complexity of future lead extraction procedures.[11] Early reports suggest that extraction is generally feasible using standard techniques, but systematic data are limited. These considerations may become particularly relevant in younger patients or those with anticipated future device revisions.

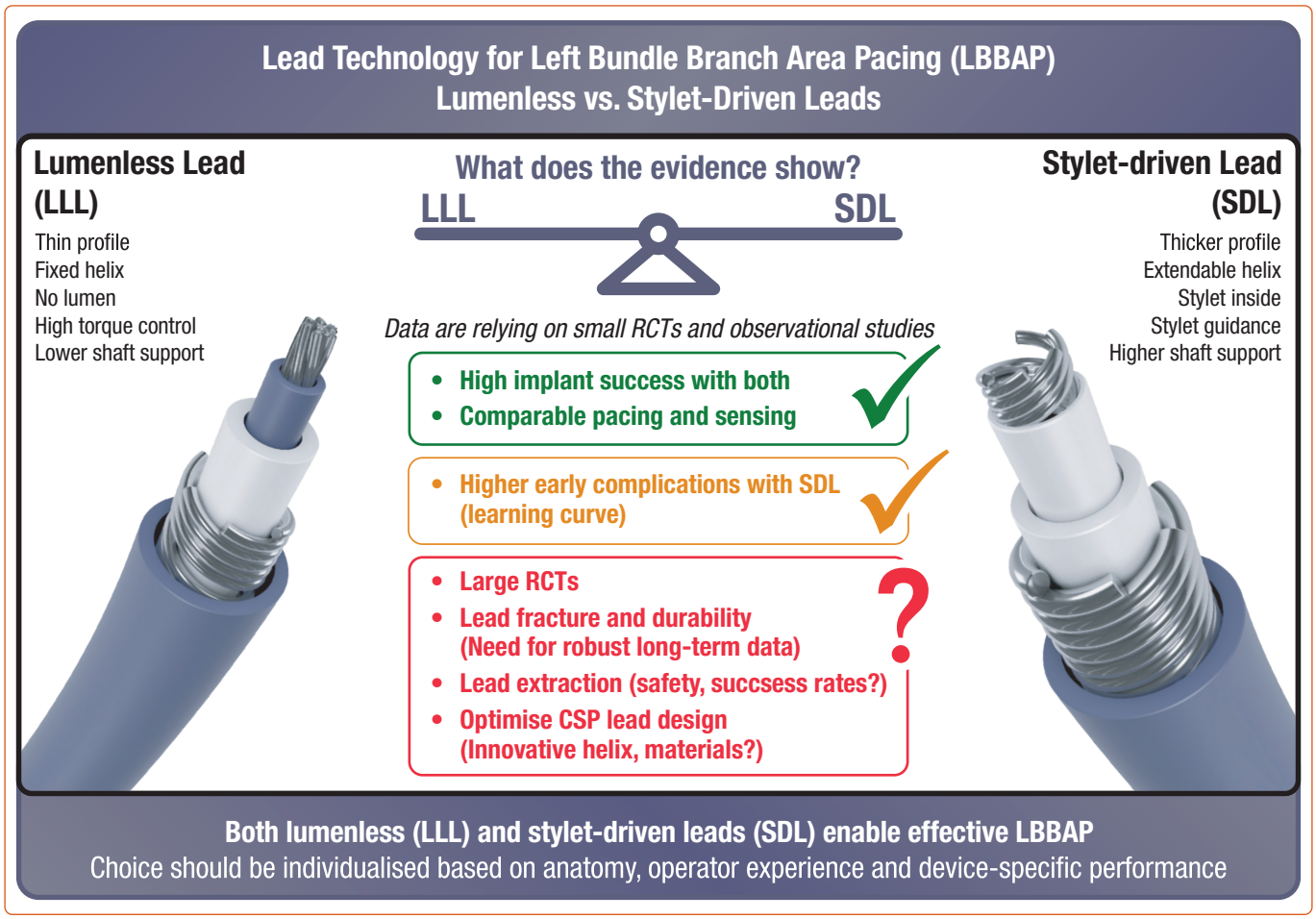
The INSIGHT-LBBA study, a large multicentre US registry, provides manufacturer-specific data for SDLs in 1122 patients undergoing LBBAP with single- or dual-chamber pacemakers.[13] Implant success was 89.6% per lead, with 96% achieving LBBAP capture (81% direct left bundle branch capture and 15% left septal capture). Primary performance endpoints at 3 months were met: 98.8% of capture thresholds were ≤2 V at 0.4 ms, 94.8% of R-wave amplitudes were ≥5 mV, and 97.7% of patients were free from lead-related complications. Long-term follow-up demonstrated stable thresholds and consistent sensing up to 24 months. Complication rates were low, including 2% deep septal misplacement and 2% right ventricular placement.

These data highlight that lead performance and safety may be manufacturer- and platform-specific, suggesting that CSP lead evaluation should extend beyond a simple LLL versus SDL comparison toward device-specific evidence. Lead performance data cannot be generalised; each manufacturer must demonstrate success rates and short- and long-

Table 1: Clinical Performance of Lumenless Leads versus Stylet-driven Leads in Left Bundle Branch Area Pacing

	Lumenless Leads	Stylet-driven Leads	Evidence Summary
Implant success	High	High	No consistent difference
Capture thresholds	Low/stable	Low/stable	Comparable
Sensing amplitudes	Adequate	Adequate	Comparable
Lead dislodgement	Low	Low to moderate	Operator dependent
Septal perforation	Rare	Rare	Technique related
Lead fracture	Rare, unknown long-term	Low, unknown long-term	Data lacking
Extractability	Feasible (limited data)	Feasible (limited data)	Major knowledge gap

Figure 1: Lead Technology for Left Bundle Branch Area Pacing Lumenless versus Stylet-Driven Leads



term performance, as exemplified by INSIGHT-LBBA's excellent results in the widest population studied. Direct comparisons remain limited because LLLs have been used for CSP over a longer period, whereas SDLs have been incorporated more recently. Long-term data on lead durability remain scarce, with lead fracture representing one of the principal concerns, particularly given the potential mechanical stress on leads positioned deep within the interventricular septum. The development of new delivery tools, sheaths, and dedicated lead designs is expected to address some of these limitations and further reduce complication rates. Based on the currently available evidence, no definitive recommendation can be made in favour of either LLL or SDL for LBBAP. Therefore, lead selection should remain individualised and guided by operator expertise, anatomical considerations and institutional experience, while further prospective studies with long-term follow-up are needed to clarify differences in safety, durability and extractability (*Table 1*).

Future Directions in CSP Lead Design

The evolution of CSP lead technology must address the unique demands of deep septal implantation and enhanced durability under repetitive mechanical stress within the interventricular septum. One key area of development is the refinement of helix design and fixation mechanisms to allow controlled septal penetration while minimising the risk of septal perforation, lead instability, or helix damage. Advances in materials and conductor design may improve long-term resistance to fatigue and fracture, an important consideration given the depth and angulation of LBBAP leads. Integration of design features that facilitate reliable confirmation of conduction system capture, such as improved sensing

electrodes or embedded diagnostic capabilities, may further enhance procedural precision and long-term follow-up.

Extraction-friendly design is another important frontier. As CSP expands to younger and more complex patient populations, future leads may incorporate features that allow safer disengagement from deep septal tissue, reducing the potential risks associated with chronic fibrotic encapsulation. In parallel, the development of purpose-built delivery sheaths and steerable systems tailored for CSP may improve procedural consistency and reduce operator dependency.

Ultimately, the next generation of CSP leads will likely reflect a shift from adaptation of conventional pacing technology toward devices specifically engineered for physiological pacing. Close collaboration between clinicians, engineers, and industry will be essential to ensure that future designs balance deliverability, electrical performance, mechanical durability, and long-term safety (*Figure 1*). The portfolio of tools, including helix locking tools, multiple sheaths and SDLs, is effective in simplifying workflows and supporting feasible, reproducible procedures with positive outcome trends.

Conclusion

CSP is an emerging and increasingly adopted therapy that offers superior physiological ventricular activation compared with conventional RVP and represents a promising alternative to BiV-CRT in selected heart failure populations. Lead technology plays a central role in the success and safety of CSP. LLLs and SDLs each offer distinct mechanical and procedural advantages, but current evidence does not establish clear superiority of one platform over the other. As CSP continues to expand across bradycardia and heart failure indications, optimisation of lead design – balancing deliverability, electrical performance, mechanical durability and extractability – will be essential to ensure the long-term safety and effectiveness of this physiological pacing strategy. ❑

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