Circulation: Arrhythmia and Electrophysiology

REVIEW

Device Programming for His Bundle Pacing

ABSTRACT: Although permanent His bundle pacing was first reported almost 2 decades ago, it is only recently gaining wider adoption, following facilitation of the implant procedure by dedicated tools. An additional challenge is programming the system, as His bundle pacing may have specific configurations and require special considerations which current implantable pulse generators are not designed for. The aim of this article is to provide practical recommendations for programming His bundle pacing, to deliver optimal therapy and ensure patient safety.

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Permanent His bundle pacing (HBP) as an alternative to pacing from the right ventricular (RV) apex was first performed in 2000 by Desmukh et al[1] and was introduced as an alternative to cardiac resynchronization therapy (CRT) by Barba-Pichardo et al in 2006.[2] Although pacing of the native conduction system has been a milestone in the quest for physiological pacing, this technique has not been readily adopted because of its technical complexity and elevated capture thresholds. Recently, a sheath with a fixed curve specifically designed to locate the His bundle (C315His catheter, Medtronic Inc, Minneapolis, MN) has greatly facilitated the procedure, with improved capture thresholds, and >90% implant success in experienced hands.[3,4] The improved implantation success rate, combined with the advent of magnetic resonance imaging conditionality of the SelectSecure 3830 lead (Medtronic) in 2017 and Food and Drug Administration labeling for HBP in July 2018, have led to a marked increase in adoption of HBP as a means of pacing. Several excellent reviews have recently been written on general aspects of HBP.[4,5]

Although implantation tools for HBP have been the focus of attention and are continuing to be developed, specific requirements for implantable pulse generator (IPG) programming and follow-up have as yet not been properly addressed. The first step in this direction has been the recent publication of recommendations to standardize definitions, implant measurements and follow-up for HBP.[6] Although timing cycles, algorithms, and programming options are likely to be adapted in the future to better suit the needs of HBP, this is unlikely to happen soon. The aim of this article is to provide practical recommendations for programming HBP.

Key Words: bundle of His ■ cardiac pacemaker, artificial ■ cardiac resynchronization therapy ■ defibrillators ■ patient safety

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GENERAL CONSIDERATIONS

There are a number of general considerations, which need to be taken into account with HBP.

His Pacing Labeling

As presently there are no IPGs available with a dedicated His pacing port, it should be made clear in the patient's pacemaker card and on the device patient information free text, that the pacing system has a His pacing lead and which port it is plugged into. This is particularly relevant when the His lead is connected to the atrial port of the IPG, which may result in confusion during follow-up, as it may be mistaken that the atrial lead has dislodged into the ventricle.

Choice of Generator and His Pacing Lead Port Position

Different IPGs and lead configurations are used according to (1) the aim of HBP, (2) the presence of a backup ventricular lead, and (3) baseline rhythm—see Table 1. Further configurations using Y-adapters are possible but are not covered here.[7] The aim of HBP may be to provide therapy in lieu of RV pacing, in lieu of biventricular pacing (eg, in case of failed coronary sinus lead implantation or to optimize prolonged atrioventricular intervals [AVI] in heart failure[8]) or as His-optimized CRT. For this last novel entity, HBP is used in addition to RV, left ventricle (LV), or biventricular pacing to optimize CRT.[9,10] HBP may only partially correct bundle branch block (BBB), and ventricular pacing may serve to further improve synchrony by activating regions which remain delayed. In case of selective His capture without correction, His-optimized CRT enables fusion pacing with consistent timing between activation wavefronts via the intrinsic conduction system and ventricular pacing,[9] even in case of complete atrioventricular block (eg, after atrioventricular node ablation).

Furthermore, the NBG (NASPE/BPEG Generic) code[11] for pacing was implemented before the era of HBP, and does not, therefore, accurately reflect His pacing, although the closest approximation is ventricular pacing. A revision of this code to accommodate for HBP would be timely.

ANALYSIS OF THE ELECTROCARDIOGRAM

Unless it is known that a His lead has been implanted, diagnosis of loss of ventricular capture may be made in some cases because of the relatively long pacing stimulus to QRS onset. Another potential source of confusion when interpreting the 12-lead ECG is the pseudo-delta wave seen during nonselective His capture (see below), which may be interpreted as the presence of an accessory pathway.

We cannot stress enough the importance of recording a standard 12-lead ECG for determining whether HBP is achieved, for evaluating capture thresholds and also the type of capture. The different types of capture have been previously defined by a consensus article[6] and are illustrated in Figure 1.

Nonselective His Bundle Capture

This is characterized by a pseudo-delta wave, reflecting local anteroseptal myocardial depolarization before the rapid activation of the ventricle via the His-Purkinje system (similar to a para-Hissian accessory pathway). It is important to analyze all 12 leads, as the pseudo-delta wave may be isoelectric in some leads, thereby masquerading as selective capture (Figure 1A). If the local ventricular electrogram on the His lead directly follows the pacing spike, this indicates nonselective capture (Figure 2). It is at present unclear if hemodynamics with nonselective capture differ compared with selective capture. Nonselective capture provides backup ventricular pacing in case of loss of His capture in patients with atrioventricular block and may also be desirable in case of His capture without correction of right BBB (RBBB) as it serves to narrow the QRS complex (see below).

Selective His Bundle Capture

This involves activation of the ventricles exclusively over the His-Purkinje system, with an isoelectric interval in all 12 leads. Paced QRS morphology may be identical to that in intrinsic rhythm or show complete or partial correction of underlying BBB. The HV interval is equal to the stimulus-V interval, although this criterion is more useful during implantation (where these intervals can be accurately measured using an electrophysiology recording system) than for follow-up. Analysis of the device intracardiac electrogram can be useful to identify selective His bundle capture which is suggested by an interval between the pacing artifact and the local ventricular electrogram (Figure 2).

Correction of BBB

In the case of baseline BBB, HBP may correct the conduction delay (sometimes to varying degrees depending on the pacing output) with either selective or nonselective His capture (Figure 1C). In case of baseline RBBB, it may be difficult to distinguish between nonselective His capture with or without correction, as capture of the right anteroseptal myocardium results in a fusion beat which narrows the QRS complex (Figure 1C).

PERFORMING HIS THRESHOLD TESTS

When performing threshold tests, it is mandatory to record a 12-lead ECG to compare QRS morphologies at different pacing outputs during the test. It is useful to start the test at maximal output and to allow at least 3 pulses at each decrementing amplitude.

Table 1. Different Device Types and Configurations for HBP

Aim	Indications	Additional V Lead(s)*	Sinus Rhythm	AF
In lieu of RV pacing	AV block Slow AF/flutter	+	CRT: His in LV port + RV + A leads in corresponding ports	DDD: His in A port + RV lead in ventricular port
		–	DDD: His in RV port† + A lead in A port	VVI: His in only port†
In lieu of BiV	Failed LV lead implantation Low likelihood of response to BiV Optimization of long AV intervals in heart failure (eg, in patients with narrow QRS)	+	CRT: His in LV port + RV + A leads in corresponding ports CRT: His in RV port† + LV + A leads in corresponding ports	CRT: His in A port + RV + LV leads in corresponding ports DDD: His in A port and RV or LV‡ lead in ventricular port
		–	DDD: His in RV port† + A lead in A port	VVI: His in only port†
His-optimized CRT	Improvement of response to CRT RBBB and selective His capture without correction	+	CRT: His in RV port† + LV + A leads in corresponding ports CRT: His in LV port§ + LV lead in RV port‖, ‡ + A lead in A port	DDD: His in A port + LV‖ lead in RV port CRT: His in A port + RV + LV leads in corresponding ports

A indicates atrial; AF, atrial fibrillation; AV, atrioventricular; BiV, biventricular pacing; CRT, cardiac resynchronization therapy pacemaker or defibrillator; HBP, His bundle pacing; LV, left ventricle; RBBB, right bundle branch block; RV, right ventricle; and V, ventricular.

*The additional ventricular lead(s) may be used for backup pacing, as an alternative therapy in case HBP is inactivated, or to optimize therapy.

In all instances, if the device is a defibrillator, and a His or LV lead is connected to the RV port, a DF-1 lead should be used, with capping of the IS-1 pin of the lead.

†With a His lead in the RV port, sensing must be acceptable.

‡Requires a bipolar (not quadripolar) LV lead. Electrical repositioning of the LV lead (eg, using the ring electrode as cathode) will not be possible.

§Alternatively, the His lead may be connected to the RV port if sensing is good and there is concern for LV dislodgment.

‖Alternatively, in case of RBBB, an RV lead may be implanted instead of an LV lead (for more shortening effect on ventricular activation time).

It is important to note transitions in QRS morphology. Transition between nonselective and selective His bundle capture can be recognized by the disappearance of the pseudo-delta wave (Figure 1A), sometimes with subtle changes in QRS morphology. Another possible transition with initial nonselective capture is a loss of His capture, resulting only in myocardial capture. In the case of 1:1 retrograde conduction, prolongation of the stimulus to P interval may be observed in this instance (Figure 1B).

There are a total of 10 different possible main transitions which are shown in Figure 3. It is important to stress that His capture may not be achieved at all, resulting in para-Hisian pacing with myocardial capture only (ie, no capture of conduction tissue). The QRS complex may nevertheless be narrower than during conventional RV pacing or even compared with intrinsic rhythm with BBB, but there is no transition in QRS morphology before loss of capture with para-Hisian pacing.

The only instances during a threshold test where no transitions in QRS morphology are observed (ie, transition directly from a paced QRS complex to loss of capture) are as follows:

1. Initial myocardial capture only (ie, no HBP achieved).
2. Initial selective His capture.
3. Near-identical thresholds for the conduction tissue and myocardium (which are not distinguished by the decremental steps during threshold tests, which are usually 0.25 V).

Impossible transitions with HBP during threshold testing are as follows:

1. Selective to nonselective His capture (the pacing output for His+RV myocardial capture needs to be higher than for His capture alone).
2. Selective His capture to RV myocardial capture (if His capture is selective, there is no initial RV myocardial capture).
3. Without BBB correction to with BBB correction (output for correction of BBB needs to be higher than without correction).

The His lead may also result in direct atrial capture. When performing threshold tests in a single-chamber mode in patients in sinus rhythm, it is possible to observe His bundle capture with higher outputs and only atrial capture with lower amplitudes, or vice-versa.

It is recommended to specify the different thresholds for correction of BBB, nonselective, selective, or RV myocardial capture.[6]

PROGRAMMING REQUIREMENTS WITH DIFFERENT CONFIGURATIONS

Programming recommendations are summarized in Table 2. The pacing mode depends on the IPG type and which port the His lead is connected to. If the His lead is connected to a ventricular port, one should bear in mind the latency in ventricular activation resulting from HV conduction, and shorten the programmed AVI accordingly. The HV interval can be measured by the stimulus

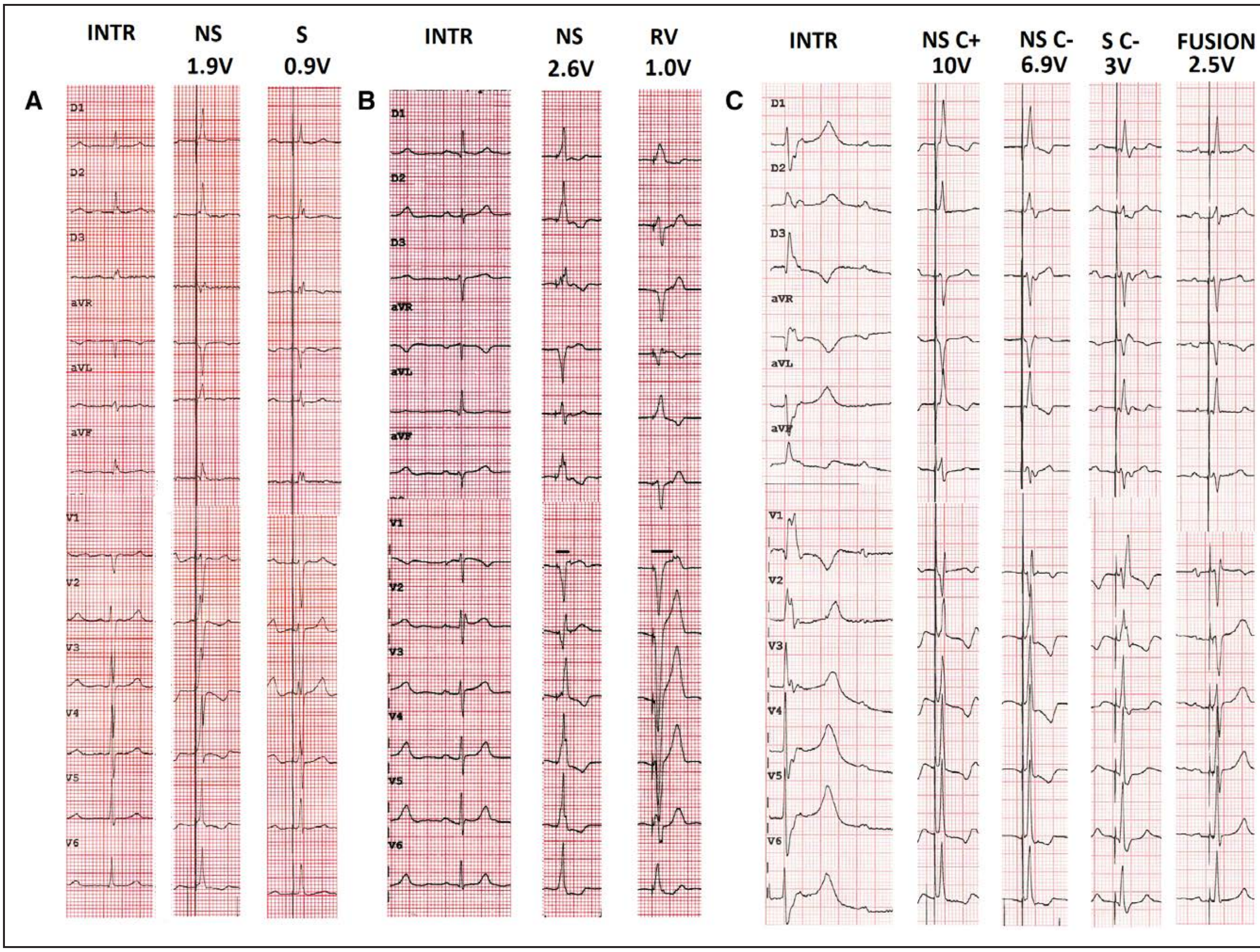

Figure 1. Examples of types of His capture at different programmed pacing outputs in 3 patients.
A, Patient in atrial fibrillation awaiting atrioventricular nodal ablation. Transition from nonselective to selective His capture. Note the presence of a pseudo-delta wave without an isoelectric interval after the pacing spike with nonselective capture, visible in aVL and the precordial leads **B**, Patient with exercise-induced Mobitz 2 atrioventricular block and narrow intrinsic QRS. Transition from nonselective His capture to right ventricular capture. Note the increase in stimulus to retrograde P duration with right ventricular capture compared to during His bundle capture (horizontal lines in lead V1). **C**, Patient in sinus rhythm with complete atrioventricular block and ventricular escape rhythm. Selective capture without correction shows a typical right bundle branch block pattern. Note how it is difficult to distinguish between nonselective capture with and without correction (a difference in QRS morphology is visible in lead II). The patient had a biventricular pacemaker with an atrial, right ventricular, and His lead (connected to the left ventricular port). Because of high capture thresholds for nonselective His capture, fusion pacing with sequential selective His capture (threshold was 1.5 V/0.5 ms) and right ventricular pacing was programmed. C+ indicates with correction; C−, without correction; INTR, intrinsic rhythm; NS, nonselective His capture; and S, selective His capture.

to QRS onset in case of selective capture. With nonselective capture, it is at present unclear if the AVI should be adjusted. It is sometimes useful to program a unipolar or extended bipolar (His tip to RV defibrillator coil or RV ring) pacing vector in order that the pacing spike is clearly visible on the surface ECG (to avoid confusion with intrinsic rhythm), and because thresholds may be lower than with bipolar pacing.[12] The tradeoff is that impedance is lower than with a bipolar vector, thereby increasing current drain. As automatic capture management algorithms are often ineffective with HBP, sufficient safety margin should be provided (eg, twice the amplitude or 3 times the duration—by analogy with myocardial pacing). In the interest of battery longevity, the safety margin is sometimes programmed lower (especially if there is backup ventricular pacing or if the patient is not pacemaker dependent), or if selective His capture (as opposed to nonselective capture) is desired. The pacing amplitude should if possible be programmed below that of the battery voltage, to avoid requirement of voltage multipliers which result in premature battery drain. In the case of high thresholds, the pulse width should be increased to, for example, 0.8 to 1.5 ms (in clinical practice, pulse widths are often programmed to 1 ms). Sensing can be an issue and should be handled differently according to which port the lead is connected to.

His Lead in the RV Port

This may involve either as follows:

1. A single-chamber system in the case of permanent atrial fibrillation or flutter.

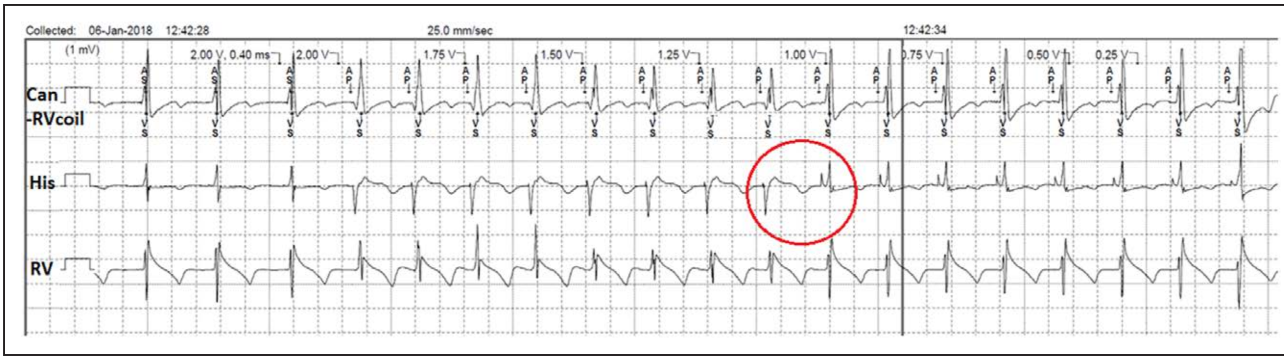

Figure 2. Threshold test with 0.4 ms pulse width with the His lead connected to the atrial port of a dual-chamber pacemaker.
Nonselective His capture down to 1 V, with selective capture thereafter (down to the minimum amplitude of 0.25 V). Note the change in electrogram morphology during the transition of nonselective to selective capture (circle). This patient had underlying right bundle branch block, which explains why sensed events by the His lead are labeled as AS and not Ab. RV indicates right ventricle.

2. A dual-chamber device and sinus rhythm (atrial+His leads).
3. A CRT device (RA+His+LV leads).

Pacing Mode

With dual-chamber systems (atrial lead+His lead in a ventricular port), the DDD(R) mode or managed ventricular pacing algorithms, such as AAI(R)/DDD(R) mode and atrioventricular hysteresis, or DDI(R) mode may be activated if the intent is to promote intrinsic conduction (although long PR intervals may result). In case of a biventricular system (atrial lead + His lead in the RV port and LV lead in the LV port), the ADI(R)/DDD(R) and AAI(R)/DDD(R) modes should not be programmed in Biotronik and Medtronic devices respectively if the intent is to pace with the LV lead (as a backup or for His-optimized CRT), as only pacing from the RV channel is currently possible in these modes. With Boston Scientific (Marlborough, MA) devices, the Rythmiq mode is currently not programmable for biventricular systems. However, Microport (Shanghai, China) CRT devices can be programmed in the SafeR mode, with pacing delivered from one or both ventricular channels.

Sensing

A major issue with a His lead connected to the RV port is sensing. Ventricular electrogram amplitude may be low (because of a far-field ventricular signal with low-frequency content which is filtered by the sense amplifier). Furthermore, oversensing of atrial or His potentials may occur, which may be potentially disastrous in a patient with complete atrioventricular block. A single-chamber pacemaker may be programmed to AAI(R), as fixed sensitivity may be set to a higher level/lower value (eg,

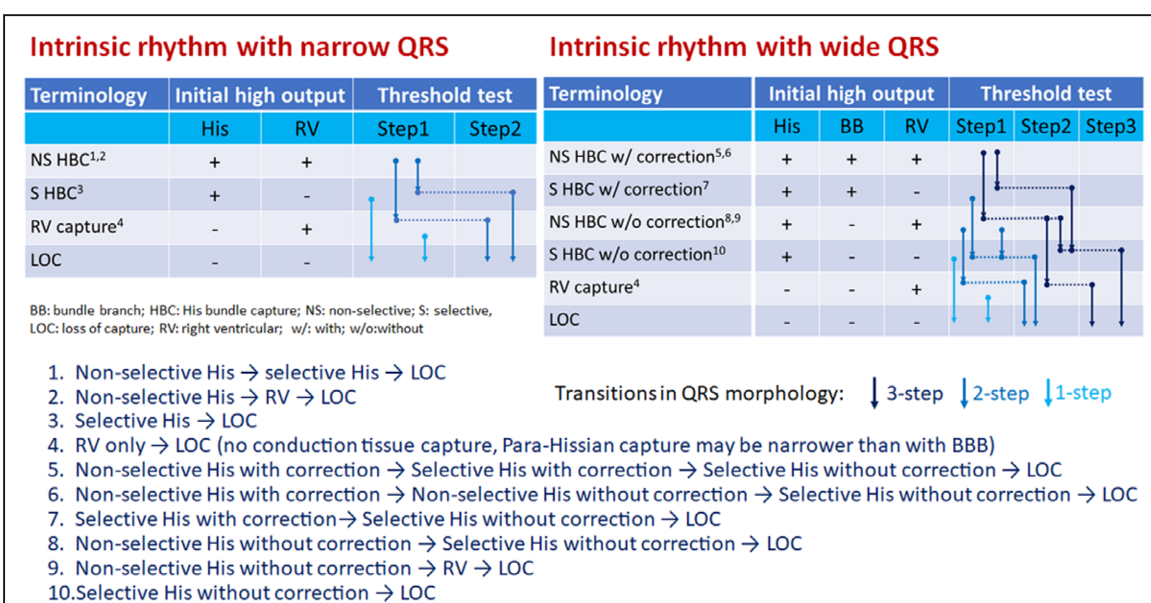

Figure 3. Summary of the main possible transitions during threshold testing of direct His bundle pacing.
Note that only initial selective His bundle capture or initial right ventricular (RV) myocardial capture (without His capture) result in a single step. Transitions may, however, be missed if the decrement in pacing output is greater than the difference in thresholds (eg, between myocardial and His thresholds). Additional minor transitions are possible in case of varying degrees of correction of bundle branch block (BBB) in a given patient, or with anodal capture if the His lead is programmed to a bipolar or extended bipolar vector, and are not shown here.

Table 2. Summary of Programming Recommendations

Parameter	Setting	Comment
Pacing mode	VVI(R)	Single-chamber system
	AAI(R)	In case of single-chamber system with low detection amplitude of the His lead - allows higher sensitivity setting than with VVI(R).
	DDD(R)	Do not program long AVI (eg, 200 ms) if the His lead is connected to the A port (because of risk of His pacing on the T-wave in case of intermittent loss of His lead capture).
	AAI(R)/DDD(R)* ADI(R)/DDD(R)	Avoid programming if His lead connected to the A port (cf comment above), or if pacing from the LV port is desired (as only RV pacing is delivered in these modes).
	DVI(R)	May be programmed if the His lead is connected to the A port, but results in pacing above the upper sensor-driven rate due to ventricular-based timing.
	DDI(R)	With the His lead in the A port, avoid programming long AVI (c.f. comment on DDD). With the His lead in the A port, results in pacing above the upper sensor-driven rate due to V-based timing.
Pacing rates	According to clinical requirement	
AVI: His lead in atrial port	Delay depends on requirement	If V backup pacing is desired, program paced AVI >Stim His-VS interval (but ≤180 ms cf. comment on DDD). If His+RV/LV pacing is desired, program a short AVI (shortest is 30 ms*).
AVI: His lead in RV/ LV port	Usual AVI minus HV interval (or stimulus to QRS onset)	AV hysteresis may be programmed if V pacing needs to be avoided.
Sensing vector	Bipolar	Unipolar may be tried if low sensing amplitude or if issues with P-wave oversensing.
Sensitivity: His lead in A port	Lowest possible (eg, 4 mV)	Program lowest sensitivity to avoid issues with oversensing of A or His potentials (V is sensed by RV lead).
Sensitivity: His lead in RV port	As usual practice	Ensure no oversensing of A or His potentials. Consider automatic sensing threshold in case of low R-waves.
Sensitivity: His lead in LV port	Not available or inactivate	V sensing by RV lead
Pacing vector	Consider unipolar or extended bipolar (if available)	Capture thresholds are usually lower than with bipolar vector, and pacing spike is visible (avoids confusion with intrinsic rhythm on ECG). Tradeoff is lower impedance compared with bipolar (ie, higher current drain).
Capture management algorithms	Off or monitor	Rarely yields accurate measurements. Must be inactivated in Medtronic CRT devices if configuration is His in LV port and RV output is subthreshold (as backup pacing during atrial, RV and LV automatic threshold tests is RV only at the programmed output*). Default setting is adaptive.* The same also applies to Boston Scientific CRT devices for the LV automatic capture threshold tests.
Ventricular safety pacing	On or off (nonprogrammable in some devices)	Consider turning off in case of His lead in A port, to avoid unnecessary V pacing (and inform of loss of His lead capture -corresponding to the percentage of AP-VP). However, presence of AV crosstalk should be tested first with worst-case scenario settings.
AdaptivCRT*	Off	Will yield suboptimal intervals. Nominal setting is Adaptive BiV and LV.
VV delay	His lead first. Delay dependant on requirement	If His-only pacing is desired (and backup pacing by the ventricular lead), program to maximum delay (with His first). In case of His-optimized CRT, program the VV delay to optimize fusion with V lead.
EffectivCRT diagnostic*	Nonprogrammable	Feature designed to indicate LV capture. If His lead in LV port, selective His capture may be indicated as ineffective pacing.
EffectivCRT during AF*	Off if His lead in LV port (unless His capture is nonselective and aim is CRT)	Feature designed to increase pacing rate during AF if ineffective pacing from the LV channel is diagnosed, which may be the case with selective His capture. Default is on.
Conducted AF response	On (if aim is CRT)	Algorithm increases pacing rate in case of V sensing during AF, to promote CRT. Will not be activated if the His lead is in the A port. Default is on.
Ventricular sense response	Off	VVT pacing designed to resynchronize conducted beats (eg, in AF). Is ineffective for HBP and will result in unnecessary battery drain. Default is on.
Noncompetitive atrial pacing	On	Algorithm designed to avoid pacing shortly after an A refractory sensed event. Does not affect HBP. Nominal is on.
PVC response	On	Post-PVC PVARP extension designed to avoid endless loop tachycardia. Does not affect HBP. Nominal is on.
Ventricular refractory period	>200 ms (usually by default)	If His is connected to the LV port with pacing only from the LV channel, RV double counting may occur if the Stim His to RVS interval >ventricular blanking.
ICD rhythm discrimination algorithms	Inactivate dual-chamber algorithms (eg, PR logic) if His lead in atrial port!	Use single-chamber discriminators instead (sudden onset, stability, morphology discrimination). Inactivate rhythm discriminators if the patient is in complete AV block.

A indicates atrial; AF, atrial fibrillation; AV, atrioventricular; AVI, atrioventricular interval; CRT, cardiac resynchronization therapy; DHBP, direct His bundle pacing; ICD, implantable cardioverter defibrillator; LV, left ventricular; RV, right ventricular; RVS, right ventricular sense; Stim, stimulation; V, ventricle; and VS, ventricular sense.

*Applicable to current Medtronic devices.

0.25 mV) compared with the interventricular interval (R) mode (usually limited to 1 mV). Otherwise, automatic sensitivity should be considered. In devices with automatic sensitivity, the maximum sensitivity varies from 0.3 mV (Abbott, St Paul, MN) to 0.5 mV (Biotronik).

Capture Management Algorithm

RV capture management algorithms are based on detection of the evoked potential, which is absent in case of selective His bundle capture. In case of nonselective capture, the algorithm yields myocardial thresholds. The feature should be either inactivated or programmed to monitor.

His Lead in the LV Port

In patients implanted with a CRT generator, the His lead is usually connected to the LV port and the RV port is connected to an RV lead (for ventricular sensing and backup pacing) or to an LV lead (because of fewer sensing issues compared with a His lead—see above). The LV port is not used for ventricular detection in Medtronic and Microport devices, and rate sensing can be programmed to only the RV channel in those manufacturers that do sense from both channels. This configuration also allows programming an extended bipolar pacing vector with the His lead, which has been shown to lower capture thresholds.[12] However, the tradeoffs in case of CRT with an LV lead in the RV port is that only bipolar LV leads can be used (whereas an IS-4 LV lead may be used if it is connected to the LV port) and that electrical repositioning (with pacing from the LV ring only) is not possible.

Pacing Mode

The device should be programmed to DDD(R) or DDI(R) modes. As mentioned above, the AAI/DDD mode should not be programmed with Medtronic devices as only pacing from the RV channel is currently possible in this mode.

Programming of Sequential Pacing

When His pacing is used in lieu of RV or biventricular pacing in patients with a His lead connected to the LV port (+ atrial + RV leads in their respective ports), the RV lead essentially serves for ventricular sensing or backup pacing in case of loss of His capture. RV pacing is, therefore, usually unnecessary or even undesirable in these instances, and His-only pacing may be the best option. However, backup RV pacing is useful in case of atrioventricular block. In this setting, sequential biventricular pacing with initial pacing from the LV channel (His lead) and an interventricular interval set to the maximum value (which varies between manufacturers from 64 ms for Abbott to 120 ms for Medico, Rubano, Italy) can be programmed to minimize undesirable RV fusion. RV pacing will usually be delivered independently of His capture because the programmed interventricular delay is shorter and the ventricular blanking period longer (usually >200 ms) than the delay between His pace to RV sense interval (reported to be 94±14 ms[13]). In some situations, fusion between HBP and RV pacing may be desirable and is a form of His-optimized CRT (Table 1). For example, His capture may be selective without correction of RBBB or with correction/nonselective capture at an unacceptably high output. Sequential RV pacing (with His pacing first, at approximately the HV interval) will result in narrowing of the QRS complex, similar to nonselective capture in this instance (Figure 1C).

Pacing Only From the LV (His) Channel

This is an option to avoid unnecessary/undesirable RV pacing (if backup ventricular pacing is not required), with the RV lead serving only for ventricular sensing or delivering implantable cardioverter defibrillator therapy. A potential issue is R-wave double counting if the delay between His pacing and RV sensing is longer than the ventricular blanking period (Figure 4A). This may result from prolonged HV intervals or noncorrected RBBB. The same phenomenon can be encountered in CRT with programming of LV-only pacing (outside the context of fusion pacing) or in case of loss of RV capture. Ventricular blanking after ventricular pacing should, therefore, be set to >200 ms (which is the default setting in most current devices). However, one should avoid prolonging ventricular blanking after ventricular sensing, to avoid undersensing of ventricular fibrillation.

Capture Management Algorithms

LV capture management algorithms are based on atrioventricular and VV conduction delays and do not usually yield accurate values when a His lead is connected to the LV port. It is important to inactivate all capture management algorithms in Medtronic CRT devices if the RV lead is programmed with a subthreshold output (eg, aiming to reduce current drain or to avoid RV capture), as backup pacing during the threshold test is only delivered with RV pacing at the programmed amplitude and may result in transient asystole in case of complete atrioventricular block.[14] This is also the case with Boston Scientific devices during the automatic LV threshold test. Other manufacturers deliver biventricular backup pulses (Biotronik) or high-output RV backup pulses (eg, 5 V/≥0.5 ms for Abbott) during LV threshold tests.

CRT Optimization Algorithms

With CRT devices, algorithms to optimize atrioventricular and interventricular delays should be inactivated when the His lead is connected to one of the ventricular ports, as these algorithms are not designed for HBP and are likely to yield suboptimal values. For instance, the Medtronic AdaptivCRT algorithm automatically adjusts the AVI based on far-field P-wave duration, or on intrinsic atrioventricular conduction delay. The opti-

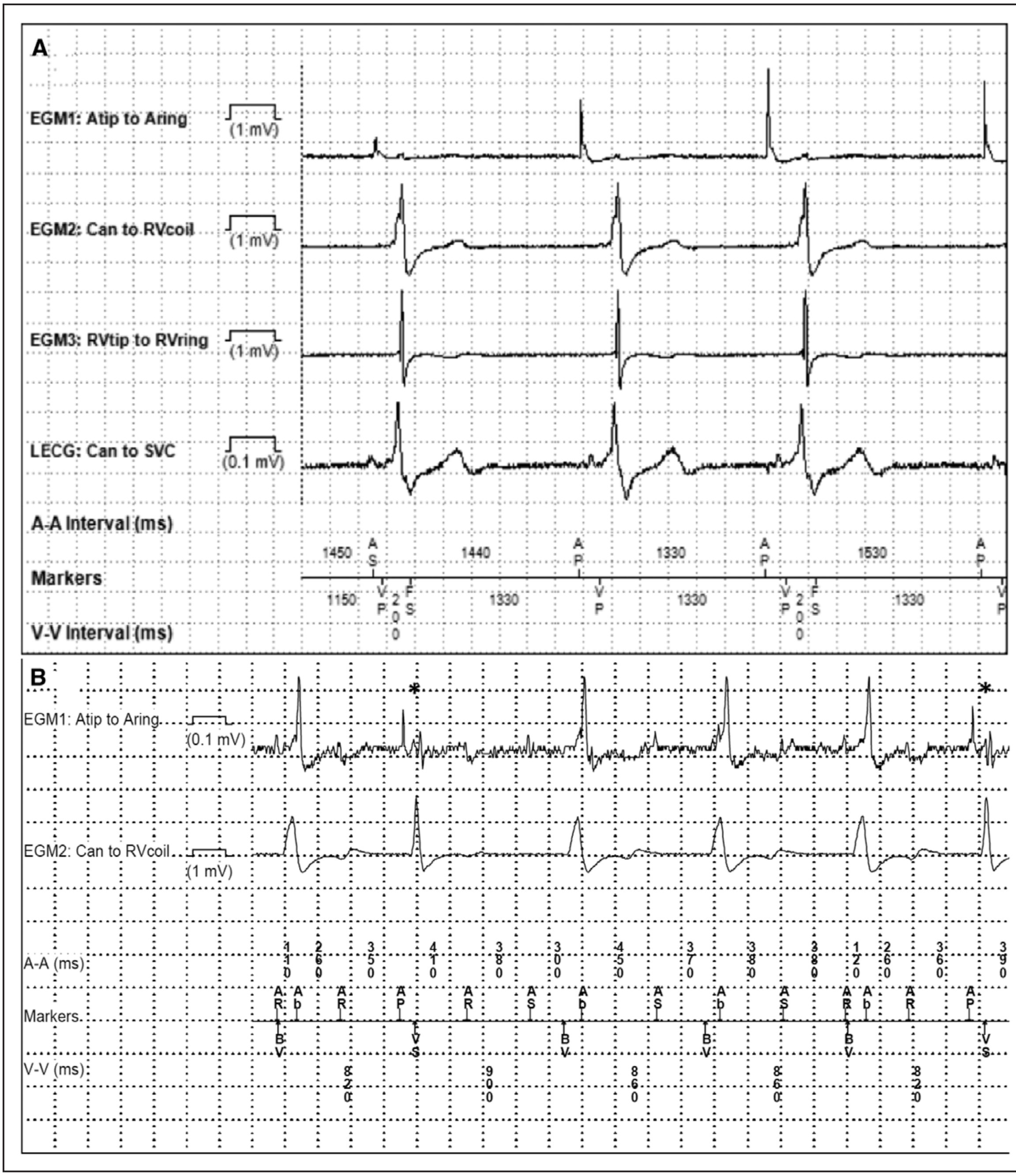

Figure 4. Oversensing issues with His bundle pacing (HBP).
A, Ventricular double counting. Biventricular defibrillator with a His lead connected to the left ventricular (LV) port. Pacing from the His lead only, with sensing from the right ventricular (RV) channel at 200 ms as shown by the fibrillation sense (FS) events (first and third cycles). Ventricular blanking was extended from 200 to 230 ms, which solved the issue. **B**, Atrial oversensing. Patient in atypical flutter who had undergone atrioventricular nodal ablation, implanted with a biventricular defibrillator and a His lead connected to the atrial port with nominal sensitivity settings. Note sensing of the atrial flutter in the His lead, with mode switch and pacing in the DDIR mode at the baseline rate of 70 bpm, mostly with biventricular pacing, and inhibition of His bundle pacing except in 2 instances denoted by the asterisks. Atrial sensitivity was decreased from 0.3 to 4mV, with resumption of His pacing.

mized AVI may be too long by about 40 to 60 ms, as the algorithm does not take into account the HV interval following the pacing stimulus before ventricular activation in HBP. Furthermore, the algorithm may propose LV-only pacing for fusion with intrinsic atrioventricular conduction, which may not be desirable in certain situations (eg, fusion with RV pacing for selective HBP with RBBB, c.f. above). Also, asystole may result in case of loss of capture in a patient with transient complete atrioventricular block (this is not an issue in case of persistent atrioventricular block as the algorithm does not activate LV-only pacing in this instance). Likewise, triggered ventricular pacing algorithms (eg, Medtronic Ventricular Sense Response) should be inactivated as they result in pseudofusion (in most CRT devices, this feature is nominally activated).

Diagnostic Features

The Medtronic EffectivCRT diagnostic algorithm evaluates whether there is LV capture based on an initial negative deflection of the intracardiac electrogram immediately following the pacing spike. In case of selective His bundle capture, the algorithm will indicate ineffective capture (because of the initial isoelectric interval in the electrogram) and effective capture in case of nonselective His capture (Figure 5).

His Lead in the Atrial Port

This configuration may cause most confusion, as sensed and paced events correspond to ventricular rather than atrial events. It is exclusively indicated in patients with chronic atrial flutter/atrial fibrillation, where there is usually no need for an atrial lead and may involve dual-chamber or CRT devices (Table 1).

Pacing Mode

The device should be programmed to a DDD(R) mode. The DDI(R) mode or DVI(R) modes (if available) are also options. A consideration resulting from short AP-VS timing with the His lead in the atrial port is the risk of pacing well above the programmed upper rate limit in case of ventricular-based timing, which may be applied in the DDIR and DVIR modes. For example, in a device with a programmed upper sensor-driven rate of 120 bpm (500 ms) and a paced AVI of 180 ms (the nominal value of current Medtronic dual-chamber devices), the VA interval will be 320 ms. If the AP-VS interval is 80 ms, the actual pacing rate will be 150 bpm (400 ms). As most devices function with atrial-based timing in the DDD(R) mode, short AP-VS intervals will not affect pacing rate in this mode.

Programming the AVI

When HBP is used in lieu of RV or biventricular pacing, a fixed paced AVI should be programmed to a value greater than the His pace—RV sense interval, which is usually 80 to 100 ms.[13] Long AVI (eg, >180 ms), as well as the AAI/DDD mode or atrioventricular hysteresis, should, however, be avoided, as these may result in His pacing on the preceding T-wave in case of intermittent loss of His capture. For example, in a device pacing at the sensor rate of 120 bpm (500 ms) with a paced AVI of 200 ms, the resulting VA interval will be 300 ms. In case of intermittent loss of capture of the His lead, an AP-VP-AP sequence will result, with risk of pacing by the His lead on the preceding T-wave. In case of consistent capture of the His lead, the sequence will be a short AP-VS interval (usually 80–100 ms[13]) with a longer VA interval (around 400 ms in the example above).

When HBP is used for His-optimized CRT, a short fixed paced AVI corresponding roughly to the HV interval (30–60 ms) should be activated, with biventricular or LV/RV pacing (the minimum programmable interval is 30 ms for most manufacturers). The optimal interval also depends on latency of ventricular capture and needs to be verified by other means such as QRS width and morphology on the ECG.

Ventricular Safety Pacing

The short AP-VS interval almost always falls within the ventricular safety pacing (VSP) window which varies between 64 ms (Abbott) and 110 ms (Medtronic), resulting in automatic delivery of ventricular pacing at the end of this window (Figure 6), with pseudofusion. Although this is not harmful, it results in unnecessary battery drain, and inactivation of this feature should be considered. However, the risk of atrioventricular crosstalk needs to be tested first by programming a maximum unipolar output in the atrial (His) channel with maximum sensitivity in the RV channel. Analyzing timing of the VS event with respect to the ventricular electrogram is crucial to distinguish between crosstalk (detection of the afterpotential of the pacing spike) and true ventricular sensing of the captured beat. The feature cannot be inactivated in Biotronik devices (with a VSP window of 100 ms) nor in Microport devices (VSP window of 95 ms), and does not exist in Boston Scientific devices, which rely on retriggerable noise windows to avoid crosstalk. Also, inactivation of VSP will indirectly inform on the percentage of loss of His lead capture, corresponding to the percentage of AP-VP events.

Sensing

Nominal sensitivity levels may lead to atrial oversensing of atrial fibrillation by the His lead resulting either in mode switch and inhibition or HBP (Figure 4B) or in irregular ventricular paced rhythm in case of intermittent atrial oversensing. It is important to stress that ventricular sensing by the His lead connected to the atrial port is not required as this is ensured by the ventricular lead. Sensitivity in the atrial channel may be programmed to the lowest level (highest value) or the DVI(R) mode may be programmed if available.

In case of intrinsic conduction and detection of the ventricular electrograms despite low sensitivity settings, sensing in the His lead usually follows shortly that of the RV lead, falling in the postventricular atrial blanking period. Current Biotronik and Medtronic devices show Ab markers for these events, which are, however, not displayed on rate histograms. Exceptions to this are presence of RBBB or ventricular premature beats, where events may be detected in the His lead before the ventricular lead, with AS events (Figure 2).

Diagnostic Features

Medtronic devices perform automatic checks for atrial lead position and warnings will appear as observations during device follow-up (based on short AP-VS intervals), but these do not affect device function for HBP (other than resulting in the inability to perform automatic capture threshold tests).

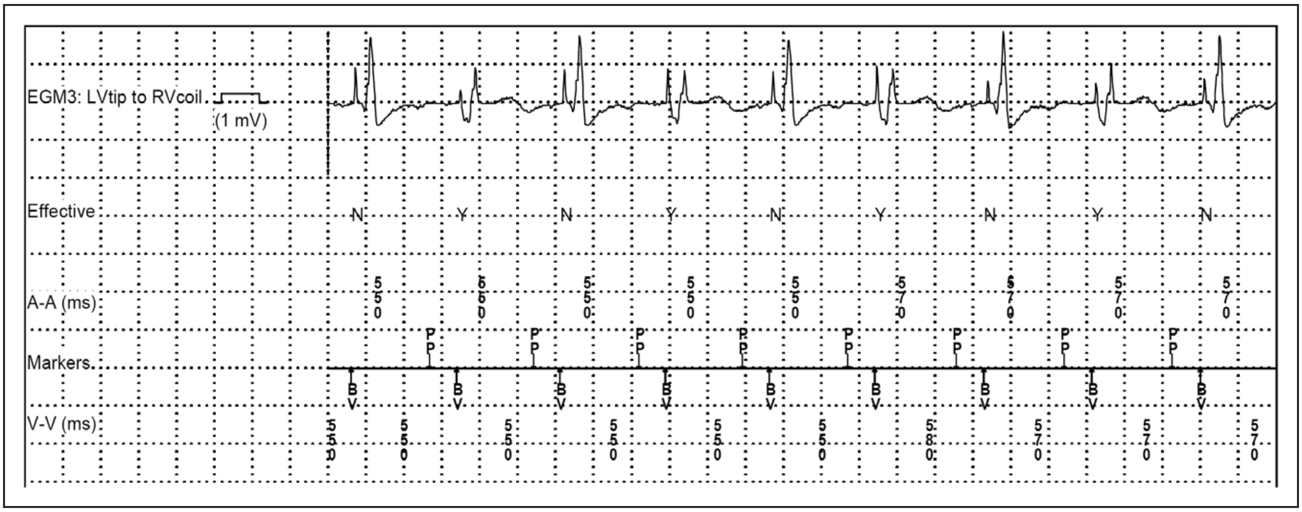

Figure 5. Episode of an ineffective ventricular capture event retrieved from a patient with a His lead connected to the left ventricular port of a biventricular defibrillator (with His pacing in lieu of biventricular pacing due to anomaly of the coronary sinus).

The Medtronic EffectivCRT algorithm annotates ineffective capture cycles with an "N," which correspond in this case to selective His capture and effective cycles with a "Y," which correspond here to nonselective capture (markers are displayed in the second line). Note the differences in electrogram morphology with QR waveforms of the effective cycles corresponding to local myocardial capture of nonselective His capture and an isoelectric interval with a far-field ventricular electrogram corresponding to the cycles labeled as being ineffective (with selective His capture). It could be deduced from the counters that the patient had selective His capture in 98% of the time (the threshold for selective capture was 1.0 V/0.4 ms and for nonselective capture, 2.75 V/0.4 ms, with a programmed output of 2.5 V/0.4 ms). This patient also had episodes of ectopic atrial rhythm originating close to the coronary sinus with short PR intervals, resulting in loss of His pacing; the preferential pacing algorithm was activated to override this rhythm (indicated by the PP annotation of the atrial marker channel).

Implantable Cardioverter Defibrillator Considerations

It should be emphasized that in implantable cardioverter defibrillators with a His lead implanted in the atrial channel, dual-chamber rhythm discrimination algorithms should be inactivated, otherwise true ventricular tachycardia may be misdiagnosed as junctional tachycardia if the ventricular electrogram is sensed by the His lead. If the His lead does not sense the ventricular electrogram (eg, because sensitivity has been set to a high value, as is generally recommended), all supraventricular tachycardia will be classified as ventricular tachycardia because of fulfillment of the V>A criterion. Single-chamber algorithms, such as sudden onset, stability, and morphology matching, should, therefore, be used instead.

UNMET NEEDS AND FUTURE DIRECTIONS

As illustrated by this article, programming of HBP may be complex, and it would be useful to have automated optimization of device parameters based on His lead connection. Adaptation of filter settings to increase sensing amplitude of far-field ventricular signals of His leads is desirable (but T-wave and atrial oversensing needs to be avoided). Specific refractory periods to prevent oversensing of atrial or His potentials, and

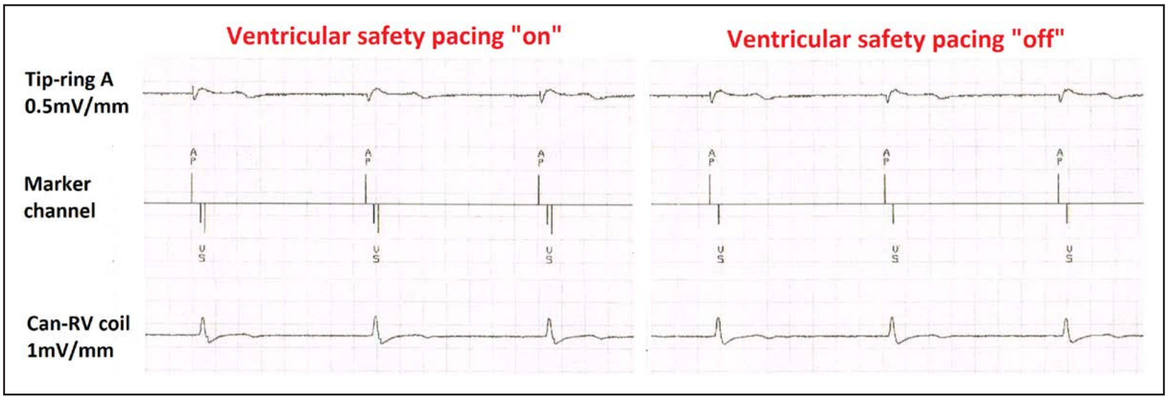

Figure 6. Medtronic biventricular defibrillator in a patient in atrial fibrillation who had undergone atrioventricular nodal ablation.

Left: Pacing by the His lead connected to the atrial port with detection of the local ventricular electrogram by the right ventricular lead after ≈80 ms, which triggers ventricular safety pacing (depicted in Medtronic devices by the double downward lines in the marker channel) at the end of the 110 ms window. **Right**: After inactivation of ventricular safety pacing (after having ruled out crosstalk), unnecessary ventricular pacing with pseudofusion is avoided.

alternatives to VSP to avoid crosstalk, would be desirable. A useful modification would be to increase the programmable interventricular delay and modify ventricular refractory periods to allow cross-chamber sensing for a defined interval after pacing to avoid unnecessary stimulation from the RV lead when the His lead is connected to the LV port. With the IS-4 standard and advent of sequential multipoint pacing, a Y-adaptor (ideally magnetic resonance imaging conditional) allowing the connection of 2 IS-1 leads (His and LV) would offer new possibilities, especially as the DF-4 standard is likely to phase out DF-1 connectors because of driving market forces. High capture thresholds are still an issue with HBP, and in addition to changes in lead design and increased battery longevity, capture management algorithms which accurately measure thresholds and adapt output accordingly would be an important step forward.

CONCLUSIONS

As a direct consequence of increasing adoption of HBP, there is a need for more widespread awareness of ECG analysis and specific programming requirements relating to this therapy. IPGs are currently not designed for HBP, and the different permutations and combinations of lead connections and system configurations leading to unusual programming settings can be confusing. The industry is no doubt going to adapt its technology to meet these challenges and facilitate device programming. However, this is likely to take time to develop and gain regulatory approval before becoming available in routine clinical practice. In the meantime, device specialists need to familiarize themselves with tailoring HBP programming to ensure safe and effective therapy for their patients.

ARTICLE INFORMATION

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