His bundle has a shorter chronaxie than does the adjacent ventricular myocardium: Implications for pacemaker programming

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BACKGROUND Strength-duration curves for permanent His bundle (HB) pacing are potentially important for pacemaker programming.

OBJECTIVES We aimed to calculate strength-duration curves and chronaxies of the HB and of the adjacent right ventricular (RV) working myocardium and to analyze zones of selective HB capture and battery current drain when pacing at different pulse durations (PDs).

METHODS Consecutive patients with permanent HB pacing were studied. The RV and HB capture thresholds were assessed at several PDs. Battery current drain and zones of selective HB capture at PDs of 0.1, 0.2, 0.4, and 1.0 ms were determined.

RESULTS In the whole group (N = 127), the HB chronaxie was shorter than the RV chronaxie. This difference was driven by patients with selective HB pacing (HB chronaxie 0.47 ms vs RV chronaxie 0.79 ms). The strength-duration curve for the HB had a lower rheobase and its steep portion started at shorter PDs, thus creating wider distance—zone of programmable selective HB pacing—between the HB and RV strength-duration curves at shorter PDs. The battery current drain was lower with pacing at PDs of 0.1–0.4 ms vs 1.0 ms. Chronaxie-adjusted PDs offered the lowest current drain.

CONCLUSION For the first time, the strength-duration curves for permanent selective and nonselective HB pacing were determined. Selective HB capture and battery longevity can be promoted by shorter PDs (0.2 ms). Longer PDs (1.0 ms) offer greater safety margin for RV capture and may be preferable if simultaneous RV capture during HB pacing is desired.

KEYWORDS Chronaxie; Current drain; His bundle pacing; Selective capture; Strength-duration

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Introduction

Permanent His bundle (HB) pacing offers most physiological spread of depolarization during ventricular pacing. It is free from many of the known detrimental effects of conventional right ventricular (RV) pacing and might reverse the clinical course and structural changes induced by RV pacing and bundle branch blocks.1–8 With the growing number of patients with permanent HB pacing devices,6–11 determination of basics of this form of pacing, such as chronaxie, rheobase, and strength-duration curves, seems important. Rheobase is defined as the smallest voltage amplitude that captures the tissue at an infinitely long pulse duration. Chronaxie is a tissue-specific measure that is used to describe the relative excitability of tissues. Chronaxie is defined as the pulse duration at which the voltage required for capture is twice the rheobase. The velocity of conduction in the HB is several times faster than that in the working myocardium, and it is known that the chronaxie is shorter for rapidly propagating tissues. Pacing at a pulse duration close to the chronaxie is most efficient with regard to optimizing battery longevity. Following this rule might be especially important during HB pacing as high pacing thresholds and faster battery depletion are seen as major drawbacks of this pacing modality. However, to our knowledge, no study has reported chronaxie values during permanent HB pacing.

Another area where knowledge of strength-duration curves for the HB might play a role is the achievement of selective vs nonselective HB capture. A few studies reported that differences in chronaxie values enable selective pacing...
of different tissues from the same electrode by using a different combination of pulse widths and voltage output\(^\text{12-15}\); whether this is also the case with HB/RV myocardium capture is not known.

We hypothesized that the chronaxie is shorter for the HB than for the adjacent septal RV myocardium and that pacing at a pulse duration closer to the chronaxie would both decrease battery current drain and facilitate selective HB capture. Our primary aim was to calculate strength-duration curves and determine chronaxies of the HB and of the adjacent RV myocardium during permanent HB pacing. Our secondary aim was to compare battery current drain and ranges of zones of programmable selective HB capture when pacing at pulse durations shorter and longer than the chronaxie.

**Methods**

The study was approved by the institutional bioethics committee. Consecutive patients who underwent permanent HB pacing device implantation in our institution in the years 2014–2018 were screened and invited to participate in the study during the device follow-up visit. In all cases, the Medtronic (Minneapolis, MN) SelectSecure 3830 lead was used for HB pacing. This is a 4.1-F, active helix, steroid-eluting lead with the cathode area of 3.6 mm.\(^2\) HB device implantation was performed using acknowledged methodology.\(^16,17\)

Basic clinical data including age, sex, comorbidities, pacing indication, pacing mode, and echocardiographic data were obtained from our prospectively maintained HB pacing database.

The first step of the study was determination of several points (minimum 4) on the strength-duration curves, separately for HB pacing and for RV pacing. For this, both the RV and HB capture thresholds were assessed throughout the whole programmable voltage range at several pulse widths during VVI unipolar pacing. Threshold assessment in each patient was performed according to uniform follow-up charts (Figure 1) that included measurements at the following pulse widths: 1.5, 1.0, 0.4, 0.3, 0.2, 0.1 ms, or the closest values available in a particular device. Additional points (@ 0.5 ms and @ 0.75 ms) were assessed when pacing at shorter pulse durations was not available in the device program or there was no capture at short pulse durations.

Simultaneous recording of all 12 standard electrocardiographic leads and observation of QRS morphology change supplemented by near-field electrogram recording with a pacemaker programmer were used as the primary method for differentiation between pure RV capture, selective HB capture, and nonselective HB capture.\(^16-18\) Programmed HB pacing method for differentiation between RV QRS and nonselective HB QRS was used when considered necessary.\(^19\) Selective and nonselective HB capture was identified according to the recently proposed criteria.\(^17\) For the purpose of this study, a patient was categorized as having selective HB capture lead position if the HB threshold was below the RV threshold with at least 1 voltage and pulse width combination. The RV capture threshold was considered to be reached at a point of the transition from RV capture to loss of capture (RV → LOC) or at a point of sudden QRS narrowing (and appearance of an isoelectric line after pacing stimulus) with pacing voltage decrease (nonselective HB → selective HB). The HB capture threshold was established by the observation of the transition from selective HB capture to loss of capture (HB → LOC) at a point of QRS widening with pacing voltage decrease (nonselective HB → RV).

For the threshold measurement protocol, we followed “ten rules for good measuring practice” formulated by Irmich,\(^20\) with the following main points:

1. Smallest possible voltage steps, as allowed by the implanted device, were used to determine the capture threshold for the RV and HB.
2. To increase precision, the threshold amplitude was recorded as an arithmetically averaged value of the last effective and the first ineffective voltage setting.\(^20-22\)
3. Voltage thresholds were expressed as the mean voltage over pulse duration (called *quantity*), where the mean voltage value was estimated using the following formula:

\[
U = \frac{1}{2} (U_{\text{lead}} - U_{\text{trail}})
\]

where \(U_{\text{lead}}\) is the leading edge voltage amplitude, set in pacemaker output setting; and \(U_{\text{trail}}\) is the trailing edge voltage amplitude estimated from the nominal output waveform at 0.4 ms, as provided by pacemaker’s technical manuals, with the assumption of linear voltage decline for the longer pulse duration.\(^20-22\)

In the second step of the study, the established RV and HB capture thresholds at different pulse widths served for the following:

1. Determination of chronaxie (\(t_c\)) and rheobase (\(I_\infty\)) using the linear regression calculation of the *quantity* vs pulse duration\(^20-23\):

\[
Q(t) = I_\infty t + I_c t_c = a + bt
\]

where

\[
I_\infty = b
\]

\[
t_c = \frac{a}{I_\infty} = \frac{a}{b}
\]

Calculation of the strength-duration curves, that is, plots of the threshold voltage vs pulse duration required to capture RV and HB.

2. Determination of the zones of selective HB capture at different pulse widths. *Zone of selective HB capture,*
expressed in volts, was defined as the range of pulse amplitudes that resulted in selective HB capture. Such zone starts with the HB threshold amplitude and ends with the RV threshold amplitude at a particular pulse width.

3. Determination of the percentage of patients who would have selective HB capture when pacing at different pulse widths when following the rules of pacing with safety margin, defined as the pacing output set at HB capture threshold + 1 V or as twice the HB capture threshold (with minimal voltage output at 1 V).

4. Calculation of current drain when pacing at different pulse widths following the rules of pacing with safety margin. Battery current drain \( I_{dr} \) (expressed in microampere-hours) by a single pacing stimulus was calculated using the following formula\(^\text{24}\):

\[
I_{dr} = \frac{U^2 \times PD}{R \times U_{battery}}
\]

where \( U \) is the output voltage (V), \( PD \) is the pulse duration (ms), \( R \) is the output impedance (\( \Omega \)), and \( U_{battery} \) is a uniform battery voltage value of 2.8 V.

**Statistical methods**

Basic and clinical data are reported as mean ± SD in the case of normal distribution, which was assessed using the

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Table 1  Basic clinical and pacing-related characteristics of the studied group (N = 127)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
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<tr>
<td>Age (y)</td>
<td>73.7 ± 11.4</td>
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<tr>
<td>Male sex</td>
<td>91 (71.6)</td>
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<td>Heart failure</td>
<td>66 (52.0)</td>
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<td>Hypertension</td>
<td>107 (86.2)</td>
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<tr>
<td>Coronary heart disease</td>
<td>54 (42.5)</td>
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<td>Diabetes mellitus</td>
<td>46 (36.2)</td>
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<tr>
<td>Pacing indications</td>
<td></td>
</tr>
<tr>
<td>Atrial fibrillation with bradycardia</td>
<td>65 (51.2)</td>
</tr>
<tr>
<td>Atroventricular block</td>
<td>25 (19.7)</td>
</tr>
<tr>
<td>Heart failure</td>
<td>25 (19.7)</td>
</tr>
<tr>
<td>Sick sinus syndrome</td>
<td>12 (9.4)</td>
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<tr>
<td>EF (%)</td>
<td>46.6 ± 14.0</td>
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<tr>
<td>LVEDD (mm)</td>
<td>54.6 (9.3)</td>
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<tr>
<td>Preimplantation QRS duration width (ms)</td>
<td>112.4 ± 25.5</td>
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<tr>
<td>Paced QRS complex width (ms)</td>
<td>119.5 ± 23.1</td>
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<tr>
<td>HB capture threshold @ 0.4 ms pulse duration (V)</td>
<td>1.16 ± 0.83</td>
</tr>
<tr>
<td>Length of follow-up (mo)</td>
<td>17.9 ± 15.8</td>
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AF = atrial fibrillation; EF = ejection fraction; HB = His bundle; LVEDD = left ventricular end-diastolic dimension.

Shapiro-Wilk test. Chronaxie and rheobase are presented as median and interquartile range. The Wilcoxon matched-pairs signed-rank test was used to compare chronaxie, rheobase, zones of programmable selective HB pacing width, and mean pulse current drain. P values of <.05 were considered statistically significant.

Results
One hundred twenty-seven patients who underwent successful implantation of HB pacing devices were studied. These patients were mostly older, with many comorbidities and moderately depressed left ventricular ejection fraction—almost all had narrow QRS complexes. HB pacing devices were implanted mainly for permanent atrial fibrillation with bradycardia or proximal atroventricular block with narrow QRS complexes. Basic clinical and procedure-related data are presented in greater detail in Table 1.

Chronaxie and rheobase
The results of chronaxie and rheobase measurements in the whole group and in the subset of selective HB pacing and obligatory nonselective HB pacing are presented in Table 2.

Selective HB pacing was seen in 99 patients (78%) and obligatory nonselective HB pacing (RV threshold always below the HB threshold at all voltage and pulse width combinations) in 28 (21%). Six patients did not contribute to strength-duration analysis because either they did not have nonselective HB capture at all or they had ≤3 myocardial capture threshold measurements that did not allow for an accurate assessment of chronaxie and rheobase values. Strength-duration curves for the RV and HB differed, as presented in Figure 2 and Table 2.

The hyperbolic curve for the HB had a lower rheobase and its steep portion started at shorter pulse widths, creating wider distance (zone of selective capture) between the curves at shorter pulse widths. The HB chronaxie was shorter than the RV chronaxie (0.53 ms vs 0.77 ms in the whole group). This was driven by the shorter HB chronaxie in patients with selective pacing (0.47 ms vs 0.79 ms, respectively) as the chronaxie in patients with obligatory nonselective capture did not differ (0.72 ms vs 0.70 ms). Patients with selective HB capture had a shorter HB chronaxie than did patients with obligatory nonselective HB capture (0.47 ms vs 0.72 ms), while there was no difference in RV chronaxie between these 2 subgroups. The calculated chronaxie range was 0.10–1.47 ms in patients with selective HB capture and 0.24–1.50 ms in patients with obligatory nonselective HB capture.

In the whole group, the RV rheobase was higher than the HB rheobase value (0.49 V vs 0.26 V); however, in the subgroup with obligatory nonselective pacing, a reversed situation was observed (0.19 V vs 0.45 V). The HB rheobase was lower in selective HB pacing (0.24 V vs 0.45 V; P = .006) and the RV rheobase was lower in obligatory nonselective HB vs selective HB (0.61 V vs 0.19 V; P = .0001) (Table 2).

Programming for selective HB pacing
The zone of programmable selective HB pacing was wider when pacing at shorter pulse durations (0.1 ms vs 0.2 ms, 0.2 ms vs 0.4 ms, and 0.4 ms vs 1.0 ms); these data are pertinent to the selective HB pacing subgroup only (Figure 3).

The percentage of patients with selective HB pacing during follow-up depends on the pulse duration and safety margin programming. More patients had selective HB capture when paced at a pulse duration of 0.1 ms or 0.2 ms.

Table 2  HB and RV chronaxie and rheobase values in subgroups

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>RV capture</th>
<th>HB capture</th>
<th>P</th>
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<tbody>
<tr>
<td>Chronaxie (ms)</td>
<td></td>
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<tr>
<td>Whole group</td>
<td>0.77 (0.58–1.15)</td>
<td>0.53 (0.32–0.76)</td>
<td>.00001</td>
</tr>
<tr>
<td>Selective HB pacing (n = 99)</td>
<td>0.79 (0.60–1.16)</td>
<td>0.47 (0.28–0.71)</td>
<td>.00001</td>
</tr>
<tr>
<td>Obligatory nonselective HB pacing (n = 28)</td>
<td>0.70 (0.46–1.03)</td>
<td>0.72 (0.51–0.88)</td>
<td>.5082</td>
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<tr>
<td>Rheobase (V)</td>
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</tr>
<tr>
<td>Whole group</td>
<td>0.49 (0.21–0.90)</td>
<td>0.26 (0.18–0.52)</td>
<td>.0001</td>
</tr>
<tr>
<td>Selective HB pacing (n = 99)</td>
<td>0.61 (0.32–1.13)</td>
<td>0.24 (0.17–0.44)</td>
<td>.0001</td>
</tr>
<tr>
<td>Obligatory nonselective HB pacing (n = 28)</td>
<td>0.19 (0.17–0.24)</td>
<td>0.45 (0.31–0.71)</td>
<td>.0001</td>
</tr>
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</table>

HB = His bundle; RV = right ventricular.
than at 0.4 ms or 1.0 ms—when the output was programmed with 1 V of safety margin (Figure 4, left panel). When the output voltage was set to twice the HB capture threshold voltage, the highest percentage of selective HB pacing cases was at a PD of 0.4 ms (Figure 4, right panel).

**Battery current drain**

The battery current drain was lower \((P = .0002)\) when pacing was programmed with a pulse duration of 0.1, 0.2, 0.4 ms vs 1.0 ms following the rule of either threshold + 1 V

\((P = .0001)\) or twice the voltage threshold (Figure 5). However, the lowest current drain of 1.4 (0.44–3.48) \(\mu\)Ah/pulse was obtained for the safety rule of + 1 V when the pulse duration was individually selected for each patient according to the calculated chronaxie (Table 3).

**Discussion**

This is the first study showing that the HB chronaxie during permanent pacing with a screw-in lead is shorter than the chronaxie of the adjacent RV myocardium. The present study also showed that this has potential practical implications as pacing at short pulse durations facilitates selective capture of the HB and results in less energy drain from the battery than pacing at 1 ms pulse width often used for permanent HB pacing.²⁵

**Strength-duration curves and chronaxie values for the RV and HB**

Despite several studies reporting strength-duration curves for the RV myocardium, the provided chronaxie values differ significantly and there is a scarcity of data with regard to the modern pacing leads. For example, while the often-cited article by Coates and Thwaites²⁶ provided a value of 0.24 ms for passive fixation, non–steroid-eluting leads with a cathode surface area of 6 mm², Dhar et al²⁷ provided a chronaxie value of 0.62 ms for more modern steroid-eluting leads with active helix leads with a smaller cathode surface area of 5.7 mm². Both these studies investigated apical RV lead positions; data on septal lead position and active fixation leads with a smaller cathode surface area are not available, to our knowledge. Differences in reported chronaxie values might have various reasons, especially the type of lead used; cathode surface area; differences in electrophysiological properties, in particular RV area; distance from the paced tissue; and methodology of measurement.²⁰,²⁸ In the present study, we have found that for the Medtronic 3830 lead at the HB capture position, the RV chronaxie is 0.77 ms—close to the values obtained by Dhar et al. However, the RV strength-
duration curve when pacing from the 3830 lead strongly depended on the pacing lead position. In the obligatory nonselective HB capture group (i.e., when the RV threshold was always lower than the HB threshold), the rheobase was 3 times lower than that in patients with selective HB capture. This can be explained by the difference in the distance of

Figure 4  Percentage of patients with selective His bundle (HB) capture is related to programmed pulse widths and safety margin.

Figure 5  Battery current drain is lower with empirically programmed shorter pulse durations or a chronaxie-based (chr.-based; see text and Table 3) pulse duration. Box plot with median and interquartile range (25%–75%).
the pacing electrode (screw-in helix) to the RV myocardium. In patients with obligatory nonselective HB capture, it can be presumed that the pacing helix is directly within the RV working myocardium (para-Hisian position) as the RV is preferentially depolarized. In the selective HB group, this distance is likely larger as the pacing helix is usually supravalvular, within the atrioventricular septum, possibly directly penetrating the HB in some cases—resulting in limited contact with the RV myocardium. It should be noted that the RV myocardium chronaxie obtained by us for this particular lead positions (HB myocardial sleeve?) might not be representative for other RV sites.

The HB chronaxie of 0.53 ms was found to be shorter than the adjacent local RV myocardium chronaxie. This might reflect the known relationship between the chronaxie and the velocity of conduction. Rapidly conducting tissues, such as nerves, have shorter chronaxies (chronaxie of 0.05 ms) than do slowly propagating tissues, such as a denervated skeletal muscle (chronaxie of 9.5–30 ms). The velocity of conduction in the HB is 3–5 times faster than that in the working myocardium; therefore, it is not surprising that the HB chronaxie was found to be shorter than the RV myocardium chronaxie. In our group, 25% of patients with selective HB pacing had a chronaxie of <0.28 ms vs only <5% of patients with obligatory nonselective HB pacing. We believe that cases with the shortest chronaxie and lowest selective HB capture thresholds (lowest rheobase) represent the possible intra-Hisian position, which most likely allow the best approximation of the true excitability of the HB. The cases with a longer HB chronaxie might represent suboptimal pacing lead positions with the pacing helix at a larger distance from the HB.

Apart from our study, we are not aware of any other published data concerning HB chronaxie during permanent pacing. A study by Fozzard and Schoenberg, concerning HB chronaxie assessed in the milieu of experimental ex vivo models reported chronaxie values of ~0.23 ms.

**Table 3** Algorithm for adjusting pulse duration programming according to the His bundle chronaxie

<table>
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<tr>
<th>His bundle chronaxie (ms)</th>
<th>Optimized pulse duration (ms)</th>
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<td>&lt;0.4</td>
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<td>0.4–1.0</td>
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<td>≥1.0</td>
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**Selective vs nonselective HB capture**

Although limited studies support the concept that nonselective HB pacing is hemodynamically equivalent to selective pacing, we do not have concrete clinical evidence. Selective HB pacing is certainly closer to physiology and offers a straightforward electrocardiographic diagnosis of the presence/loss of HB capture and also allows to easily offset the HV interval from atrioventricular delay during DDD pacing. Moreover, nonselective HB capture, especially in patients with a prolonged His-ventricle interval and/or uncorrected bundle branch block, occasionally results in a large degree of direct myocardial depolarization and broad QRS complexes of >150 ms, and it is reasonable to suspect that such nonselective HB pacing may be hemodynamically inferior to selective HB pacing with narrower QRS complexes.

It was shown that stimulation of the vagus nerve with different pulse widths excites different nerve fibers within the nerve because of the differences in chronaxie between them. Similarly, in the pacing arena, differences in chronaxie were explored for selective pacing of the left ventricular myocardium and avoidance of phrenic nerve capture during cardiac resynchronization therapy. It was observed that the faster conducting tissue (ie, phrenic nerve) had a shorter chronaxie than did the left ventricular myocardium (0.22 ms vs 0.47 ms). We believe that the phrenic nerve as a more distant structure has a higher rheobase and pacing with the lowest possible amplitude avoids its capture during cardiac resynchronization therapy. In patients with permanent HB pacing, the situation is reversed: the structure that we might desire to pace selectively (HB) has a faster conduction velocity and shorter chronaxie than did the structure that we might want to avoid capturing (RV). This is why selective capture is facilitated with pacing at shorter pulse widths at which the distance between HB and RV strength-duration curves is greater since the steep portion of the RV strength-duration curve starts later (see Figure 2). In other words, the zone of selective HB capture is widening with shortening of the pulse duration (Figures 2 and 3). The present study shows that there is an increasing percentage of patients with selective HB pacing when shorter pulse widths are programmed (Figure 4). Of note, in our center we observed a higher percentage of patients with chronic selective HB pacing (59%) than reported in studies by Zanon et al, Kronborg et al, and Sharma et al 2015 (28%, 12.5%, and 45% of patients with selective pacing, respectively). These differences might be explained by differences in the customs of pulse width programming or studied population. It is our current practice to promote selective HB capture by empirical programming of the pulse duration to 0.2–0.3 ms, unless this would result in pulse amplitude of greater than the battery voltage. However, if simultaneous backup RV capture is desired for clinical reasons (distal atrioventricular block), then the long pulse duration (1.0 ms) should be preferred as it offers greater safety margin for RV capture.

**Current drain during HB pacing**

In light of higher capture thresholds, lack of pacemakers dedicated for HB pacing with a larger battery, and automatic capture algorithms capable to recognize HB capture, it is of paramount importance to optimize battery longevity with appropriate programming. Chronaxie values during HB pacing have a broader range than those during conventional RV pacing. The default pacemaker values for pulse width—0.4–0.5 ms or especially the 1.0 ms that is often used in HB pacing—can be significantly far from the optimal (ie, close to the chronaxie). It has to be kept in
mind that at the constant voltage, changing the pulse duration from 0.2 to 1.0 ms increases the battery drain 5 times. Using longer pulse widths might be deceptive as to the real current drain because of the lower programmed output amplitude.

Our study shows that the lowest current drain can be achieved when the programming of the pulse duration is guided by the chronaxie, regardless of the chosen safety margin (+1 V or twice the voltage threshold).

Limitation

The provided chronaxie values are for the Medtronic 3830 lead and might be different if a different lead is used for HB pacing.

The studied group mainly consisted of patients with narrow native QRS complexes who were not pacemaker dependent; in patients with complete infranodal heart block and/or left bundle branch block where recruitment of distal His-Purkinje (HB) fibers is required, different HB chronaxies might be present. However, the patients with infranodal block or left bundle branch block who were included in the selective HB group and had distal capture did have a short chronaxie, although nonselective HB pacing may be preferred in this population for clinical reasons.

The impact of the voltage multiplier on the current drain was not assessed. In patients with devices using a voltage multiplier, programming a pulse width of 0.2 ms might result in voltage programmed to greater than the battery voltage (2.8–3.0 V) and consequently in higher current drain than when programming 1 ms pulse width and the amplitude less than the battery voltage. This is less of an issue in modern pacemakers, which have charge pumps rather than voltage multipliers.

Conclusion

Novel methods of cardiac pacing present new challenges and require a thorough understanding of the basics of the new type of pacing. The present study shows that permanent HB pacing is characterized by a shorter chronaxie and lower rheobase as compared with RV pacing from the same lead. This might have practical implications, such that permanent HB pacing can be optimized with regard to obtaining selective HB capture and improving battery longevity by programming pulse durations according to the estimated HB chronaxie. However, if simultaneous backup RV capture is desired for clinical reasons, then the long pulse duration should be preferred as it offers greater safety margin for RV capture.

References


