The Strength-Duration Curve and Its Importance in Pacing Efficiency: A Study of 325 Pacing Leads in 229 Patients

STEPHEN COATES and BARNABY THWAITES

From the Department of Cardiology, Wansbeck General Hospital, Ashington, Northumberland, the United Kingdom

COATES, S., ET AL.: The Strength-Duration Curve and its Importance in Pacing Efficiency: A Study of 325 Pacing Leads in 229 Patients. *Pacemaker battery life is dependant on programmable parameters, principally pulse amplitude and pulse duration. High factory default settings cause excessive current drain. The strength-duration curve relates pacing threshold to pulse duration. The most energy efficient pacing occurs at chronaxie, a value of pulse duration derived from the curve. Strength-duration curves were calculated for 325 acutely implanted pacing leads. Chronaxie and rheobase were compared for atrial and ventricular leads. Chronaxie was compared with actual programmed pulse duration. There were 101 atrial and 224 ventricular leads, all passive fixation. The curve fit was good, (mean error ± SD) 0.024 ± 0.06 V for atrial curves and 0.008 ± 0.034 V for ventricular curves. Mean (± SD) atrial and ventricular chronaxies were 0.24 ± 0.07 ms and 0.25 ± 0.07 ms, respectively. A "Z" value of 1.4 indicated that chronaxies might have been from the same population. Mean (± SD) atrial and ventricular rheobases were 0.51 ± 0.2 V and 0.35 ± 0.13 V, respectively. A "Z" value of 7.1 ($P < 0.001$) suggested atrial and ventricular rheobases were from differing populations. All patients had factory default pulse durations of 0.45 ms or 0.5 ms, exceeding acute chronaxie by a factor of two, thus, demonstrating suboptimal pacing. We conclude that understanding the strength-duration curve is critical. Sensible programming of other pacing functions optimizes longevity. Battery drain is reduced by programming pulse duration to chronaxie with a doubling of voltage threshold at this point to achieve a safety margin. Further study of chronaxie drift with time is required. (PACE 2000; 23:1273–1277)*

pacing, pacemaker, strength-duration curve

Introduction

It is probable that maximal pacemaker battery life is not realized in the majority of paced patients. This study illustrates the key position of the strength-duration curve in pacing practice. Excessive energy drain from pacemakers leads to shortened battery life with a consequent reduction in time to replacement of the pulse generator. Two principal pacing waveform parameters, voltage and the pulse duration for which that voltage is applied, account for a large proportion of that energy drain, longevity being inversely proportional to lead current. These parameters are programmable in all modern pacemakers allowing for optimization of their settings. Factory defaults in these settings are high to provide safety margins for the rise in threshold after implantation and are usually left unchanged.[1] The energy required for cardiac stimulation varies with pulse duration as a U-shaped curve. The minimum of this curve is at chronaxie, which indicates the most efficient pulse duration for stimulation. Chronaxie is defined as the pulse duration at twice the rheobase. Rheobase is the stimulation threshold at infinite pulse duration; that is, as pulse duration is increased there comes a value of voltage (or current) below which threshold will not fall. Lapique[2] in 1909 was the first to describe the hyperbolic correlation between pulse duration and mean stimulus. Figure 1 shows an example of this hyperbolic strength-duration curve with rheobase and chronaxie highlighted and the energy curve superimposed.

Strength-duration curves can also be plotted as a linear function where the y-axis represents the product of mean voltage and pulse duration and the x-axis is the pulse duration. From this graph derived by Weiss[3] in 1901, the slope gives the rheobase and the chronaxie is calculated from the y-intercept divided by the slope.

To set the pacing output stimulus to a pulse duration equal to chronaxie would then conserve energy and prolong pulse generator longevity. An adequate safety margin can be provided by setting a pulse amplitude of twice voltage threshold as measured at chronaxie.

Address for reprints: Mr. Steve Coates, Medical School, Framlington Place, Newcastle upon Tyne NE2 4HH, UK. Fax: 44 (0) 1670 529452; e-mail: coates_steve@hotmail.com

Received July 27, 1999; revised December 20, 1999; accepted January 26, 2000.

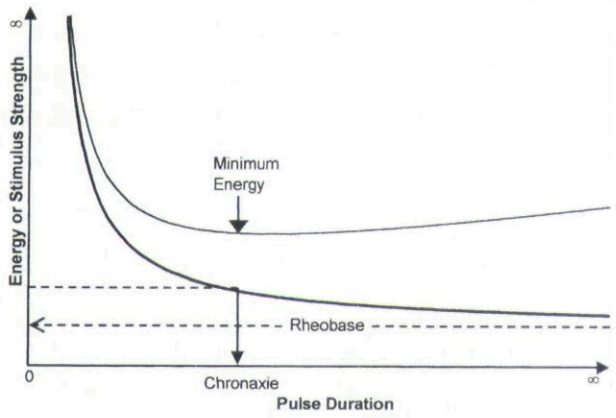

Figure 1. *Energy and stimulus strength versus pulse duration. The horizontal axis is the pulse duration. The vertical axis is the energy or stimulus strength delivered. Rheobase is shown as the lower hashed line and the upper-hashed line represents voltage (or current) at twice rheobase. The intersection of this value with the curve defines chronaxie. An energy curve at top illustrates a nadir at chronaxie.*

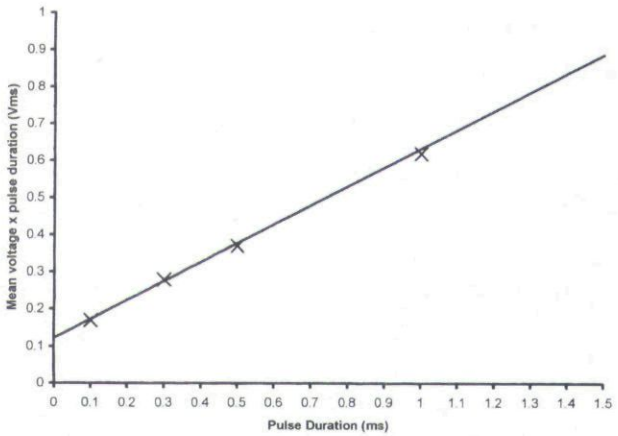

Figure 2. *Example of the Weiss linear strength-duration curve derived from data obtained from one of our patients. The crosses represent the four data points calculated as the product of mean threshold voltage and pulse duration. The slope of the curve gives the rheobase, and the chronaxie is derived from the value of the y-axis intersection divided by the slope.*

The aims of this study were to (1) construct a strength-duration curve from four simple threshold measurements preoperatively and assess its accuracy, (2) derive the chronaxie and rheobase for each lead, (3) compare actual pulse duration settings with individual chronaxies for a set of patients to see if pacing waveforms were optimized for energy, (4) consider the relationship of acute strength-duration curves to the mature lead, and (5) consider other possibilities to prolong battery life.

Patients and Methods

Data were analyzed from 325 pacing leads (101 atrial and 224 ventricular) in 229 consecutive patients (141 men, 88 women; mean age 76 years, range 28–98 years) with pacemakers implanted at our hospital between December 1993 and January 1999. Active fixation leads were excluded as they have different acute characteristics. Patients had voltages delivered at implantation using a Biotronic Pacing System Analyser ERA 300 at pulse durations of 0.1 ms, 0.3 ms, 0.5 ms, and 1 ms. The mean output voltage was measured using a Tektronix 2445A oscilloscope. Voltages were set to achieve capture and then decremented in 0.1-V steps until capture was lost. Threshold was taken as the voltage at 0.1 V above loss of capture. Each threshold voltage was multiplied by the pulse duration to give four data points. The Weiss linear model of the strength duration curve was then adapted to the data points using "method of least squares." Figure 2 shows an example of the linear strength-duration curve from data obtained from one of our patients. The quality of the fit of the curve was determined by finding the average difference between the measured points and those points on the calculated curve at the same pulse durations. Chronaxie and rheobase were then derived for each set of data points and their means and standard deviations calculated. Z values were used to see if atrial and ventricular data were from the same population. A P value < 0.01 was taken as significant.

Results

The 229 patients comprised 101 atrial leads and 224 ventricular leads. All were passive fixation in design, and the different leads are shown in Table I. Table II shows the indication for pacing in these patients.

The curve fit gave a mean error $\pm$ SD of 0.024 $\pm$ 0.06 V for atrial curves and 0.008 $\pm$ 0.034 V for ventricular curves when compared to measured points. This gave a good accuracy as the voltage thresholds were measured to a resolution of 0.1 V.

Comparison of atrial and ventricular chronaxies and rheobases showed that while chronaxies may have come from the same population ($Z = 1.4$) the probability of rheobases doing so was exceedingly small ($Z = 7.1$, $P < 0.001$). Atrial and ventricular data were therefore treated separately.

Table III shows the mean and standard deviations of rheobase and chronaxie in the atrial and ventricular leads as determined by the calculated strength-duration curves. It can be seen that atrial

Table I.

Lead Type and Electrode Surface Areas for Implanted Atrial and Ventricular Leads

Atrial Leads Total n = 101		Ventricular Leads Total n = 224	
Surface area shown in brackets as (proximal electrode area, distal electrode area) mm^2			
1 Sorin S200 B	(35,8)	12 Sorin S80	(35,6)
62 Sorin S80 JB	(35,6)	71 Sorin S80 TB	(35,6)
26 Biotronik TIJ 53 BP	(48,6)	80 Biotronik TIR 60 BP	(48,6)
6 Biotronik JP 53 BP	(48,6)	58 Biotronik NP 60 BP	(48,6)
5 Intermedics 438 05	(50,10)	2 Pacesetter 1401 T	(30,9)
1 Intermedics 430 05	(50,10)	1 Pacesetter 1470 T	(30,2.3)

Table II.

Indication for Pacing in the 325 Patients

Reason for Pacemaker Implantation	Number of Patients
Sick sinus syndrome	69
First-degree AV block	2
Second-degree AV block Type 1	7
Second-degree AV block type 2	23
Third-degree AV block (narrow QRS)	29
Third-degree AV block (wide QRS)	40
Bifascicular block	7
Trifascicular block	7
Slow atrial-fibrillation	22
AF prevention	2
Vasovagal syncope	2
Carotid syncope	7
Tachybrady	7
Junctional brady	1
Hypertrophic cardiomyopathy	2
Unspecified	2

and ventricular chronaxies are at approximately 0.25 ms. This value is in keeping with other chronaxie measurements with similar surface areas of distal electrodes.[4,5] Most of the patients in the study had a pulse duration set at 0.45 ms or 0.5 ms (common factory defaults) from implantation suggesting that pulse durations were too long and wasteful of energy, even though voltage pulse amplitudes are routinely reduced as possible at the 6-month postimplantation pacing check (to the available programmed setting closest to twice voltage threshold). Pulse durations set at chronaxie are at minimum energy. If pulse durations are set higher than chronaxie, then more energy is being used than is required.

Figure 3 shows a plot of the energy wasted if chronaxie is less than the factory pulse duration default setting of 0.5 ms (Appendix A). With a chronaxie of 0.25 ms (the mean chronaxie), 12.5% more energy was used than necessary. At low chronaxies (2 SD below the mean) up to 73% more energy was being wasted.

Table III.

Means and Standard Deviations for the 101 Atrial and 224 Ventricular Leads

	Atrial Data	Ventricular Data
Mean rheobase (V)	0.51	0.351
Standard deviation (V)	0.2	0.13
Mean chronaxie (ms)	0.24	0.25
Standard deviation (ms)	0.07	0.07

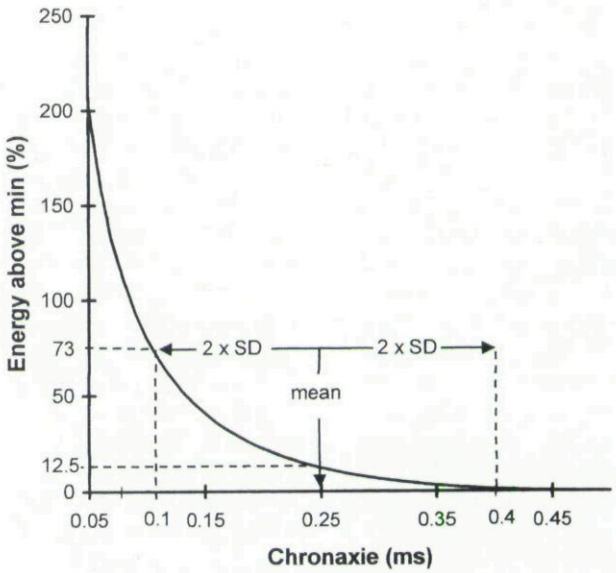

Figure 3. *Percentage energy used above the minimum required for given chronaxies and at a fixed pulse duration of 0.5 ms. If chronaxie is in fact 0.25 ms, actually pacing at a pulse duration of 0.5 ms represents 12.5% excess energy usage. If the chronaxie is 2 SD < 0.25 ms, there is 73% energy wastage.*

Discussion

In our study, chronaxies were derived from threshold values measured at four stimulation pulse durations at implantation. Since only four data points were used for the curve fit, a source of error was introduced. Nevertheless, the closeness of the fit was good, as suggested by the small mean error and standard deviation of the error. The chronaxie values obtained are likely to be accurately representative of the acutely implanted lead.

Since optimization of stimulation settings refers to the chronic stable lead that pertains after 6–12 weeks, the behavior of chronaxie after implantation is important. This is to some extent unclear. Some authors state that after an initial increase, chronaxies fall to 80%–100% of their original value.[5,6] Others suggest that chronic chronaxies are the same as acute values or slightly larger.[7,8] If the former occurs, using acute chronaxie to optimize the chronic settings would be safe. However, a significant increase would lead to unsafe pacing if the acute chronaxie was used.

Crossley et al.[9] found that optimizing pulse parameters in terms of safety margins gave a potential extension of time to reimplantation of 4.25 ± 2.14 years. A better method of lead energy optimization may, therefore, be to measure chronic chronaxies. This would require a pacemaker to provide fine 0.1-V steps in programmable values and several programmable pulse durations.

In general, the pacemakers of the patients forming this study group underwent simple energy conservation 6 months after implantation by measuring the voltage stimulation threshold at default pulse durations (0.45 ms or 0.5 ms) and doubling the voltage threshold. This was repeated at each 6-month follow-up. This leaves untapped further energy saving potential as default pulse durations are clearly well above the average chronaxies (0.25 ms) obtained at implantation.

Although energy is optimized at pulse durations set to chronaxie, a high threshold value at this point may mean that the pulse generator may not have the capability to produce a pulse large enough to satisfy amplitude safety margins, or the voltage required may stimulate the pectoral muscles (in unipolar pacing) or the diaphragm (in either a unipolar or a bipolar system). In this case a limited reduction in required pulse amplitude may be achieved by increasing pulse duration beyond chronaxie at the expense of energy.

Battery longevity is related to other important factors. High impedance leads (> 1,000 Ω) can reduce lead current thus maximizing battery life. Sensible programming of lower rate and atrioventricular delay can reduce the frequency of paced complexes and minimize the occurrence of ventricular pseudofusion (coincident ventricular pacing impulse with intrinsic atrioventricular conduction). The use of the atrial pacing (AAI) mode in patients with intact atrioventricular conduction saves all ventricular circuitry. Minimal effective use of the rate response mode is also important.

Battery longevity is given as $L = [C/D] \times 114.2$, where L = longevity in years, C = battery capacity ampere-hours (Ah), and D = current drain (μA) (114.2 constant to convert Ah to microampere-years). Thus, a 0.2=Ah battery with 2-μA current drain results in an 11.4-year longevity. The largest longevity savings are elicited in practice with the greatest voltage output reductions possible, and this should be done at the chronaxie pulse width.

Conclusion

We have shown that an accurate strength-duration curve can be derived at implantation from four data points. Also, with a sufficiently programmable pulse generator, it can be telemetrically derived at any time thereafter. The data clearly demonstrated that factory default pulse durations (around 0.5 ms) are too long and energy inefficient. The balance of evidence suggests that the acute chronaxie is a reliable guide to chronic values, and so setting the chronic pulse duration to acute chronaxie and setting pulse amplitude to double voltage threshold at chronaxie will result in substantial energy savings. Put another way, the cost per year of pacing can be reduced. However, a clearer definition of chronaxie drift with time in future studies is desirable. Understanding of the strength-duration curve is highly rewarding in enhancing everyday pacing practice.

Acknowledgments: The authors thank Shelly Thwaites, Jenny Lewis, and Gloria Wilson (cardiac technicians) for recording data points during implantation and Dr. P.D. Higham, Consultant Cardiologist, for study of patients under his care.

Appendix A

Energy Equations

Energy E is the time integral over the product of voltage and current. For modern constant voltage generators, at constant impedance, the equation for energy E approximates to the product of the mean voltage , mean current and pulse duration d[10]:

$$\mathbf{E} = \bar{\mathbf{V}}\bar{\mathbf{I}}_d \qquad (1A)$$

The mean voltage and current necessary to achieve capture is related to the chronaxie and the rheobase.[2] The voltage and current curves may differ in shape and so have different values of chronaxie and rheobase. The relationship be-

tween energy E and voltage and current rheobases is given by:

$$\mathbf{E = V_\infty I_\infty} d\mathbf{(1 + T_{ic}}/\boldsymbol{d}\mathbf{)(1 + T_{vc}}/\boldsymbol{d}\mathbf{)} \qquad (2A)$$

Where

$\mathbf{V_\infty}$ = voltage rheobase
$\mathbf{I_\infty}$ = current rheobase
$\mathbf{T_{ic}}$ = current chronaxie
$\mathbf{T_{vc}}$ = voltage chronaxie

To find the energy minimum this equation is differentiated and equated to zero. This gives an energy minimum at $\mathbf{d} = \sqrt{(\mathbf{T_{ic}}\ \mathbf{T_{vc}})}$. We have assumed that current and voltage chronaxies are comparable. This is a safe assumption if electrodes are made of nonpolarizable material[4] (modern day electrodes have minimized polarization[11]).

When $\mathbf{T_{ic}} = \mathbf{T_{vc}}$ then Equation A2 reduces to

$$\mathbf{E = V_\infty I_\infty} d\mathbf{(1 + T_{vc}}/d\mathbf{)^2} \qquad (3A)$$

This has an energy minimum (E_{min}) at $d = T_{vc}$. When this is substituted into Equation A3:

$$\mathbf{E_{min} = 4V_\infty I_\infty T_{vc}} \qquad (4A)$$

Dividing Equation A3 by Equation A4 gives the proportional change in energy above minimum due to variation in pulse duration or chronaxie:

$$\mathbf{E/E_{min}} = d\mathbf{(1 + T_{vc}}/d\mathbf{)^2/4T_{vc}} \qquad (5A)$$

With a pulse duration set at the manufacturers default setting of 0.5 ms, $\mathbf{E/E_{min}}$ varies only with chronaxie:

$$\mathbf{E/E_{min} = 0.125(1 + T_{vc}/0.5)^2/T_{vc}} \qquad (6D)$$

With $\mathbf{T_{vc}}$ = 0.5 ms and therefore with pulse duration at minimum energy, $\mathbf{E/E_{min}} = 1$. If chronaxie is < 0.5 ms then $\mathbf{E/E_{min}}$ will rise proportionally. This may be expressed as a percentage and shows the excess energy ($\mathbf{E_{excess}}$) used due to a lower than optimum chronaxie:

$$\mathbf{E_{excess} = (E/E_{min} - 1) \times 100(\%)} \qquad (7A)$$

This curve is shown in Figure 3.

References

1. Irnich W, Kramer E, Muller R. The programming of cardiac pacemakers: Wish and reality. Deutche Med Wochenschr 1991; 116:601–605.
2. Lapique L. Definition expérimentalle de l'excitablilité. Proc Soc Biol 1909; 77:280–285.
3. Weiss G. Sur la possibilité de render comparable entre eux les appareils cervant à l'excitation électrique. Arch Ital Biol 1901; 35:446.
4. Irnich W. The chronaxie time and its practical importance. PACE 1980; 3:292–301.
5. Furman S, Garvey J, Hurzeler P. Pulse duration variation and electrode size as a factor in pacemaker longevity. J Thorac Cardiovasc Surg 1975; 69:382–389.
6. Smyth NPD, Tarjan PP, Chernoff E, et al. The significance of electrode surface area and stimulating thresholds in permanent cardiac pacing. J Thorac Cardiovasc Surg 1976; 71:559–565.
7. Barold S. Modern Cardiac Pacing. Armonk, NY, Futura Publishing Co., 1985, p. 43.
8. Hynes JK, Holmes DR, Merideth J, et al. An evaluation of long-term stimulation thresholds by measurement of chronic strength duration curves. PACE 1981; 4:376–379.
9. Crossley GH, Gayle DD, Simmons TW, et al. Reprogramming pacemakes enhances longevity and is cost-effective. Circulation 1996; 94(Suppl. 2):245–247.
10. Barold S. Modern Cardiac Pacing. Armonk, NY, Futura Publishing Co., 1985, p. 36.
11. Ellenbogen KA. Cardiac Pacing. 2nd edition. Malden, MA, Blackwell Science, 1997.