Fundamental Electrical Relationships:
Ohm’s Law, Strength Duration Curve &
Factors Affecting Thresholds

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Arrhythmia Technologies Institute
Outline

- Ohm’s Law
  - Voltage, current and resistance (impedance)
  - Energy and power
  - Clinical relevance

- Strength duration curve
  - Rheobase
  - Chronaxie
  - Clinical relevance
Ohm’s Law

\[ V = I \times R \]
\[ I = \frac{V}{R} \]
\[ R = \frac{V}{I} \]

The equation uses current in the form of Amps. In pacing current is expressed in mA.
Fundamentals of Electronics

- **Voltage (V):** force moving the current: electromotive push
- **Current (I):** flow of electrons through a circuit mA
- **Resistance (R) / Impedance:** opposition to current flow: unit of measure: Ohm (Ω)
Low Resistance = high current flow
High Resistance = low current flow
Ohm’s Law: Pacers vs ICD’s

Typical range for pacemaker voltage 1.0-5.0 V
Typical range for ICD voltage 50-800 V

Typical range for pacemaker current 2-16 mA
Typical range for ICD current 1,000-75,000 mA

Typical range for pacing lead impedance: 300-1200 Ohms
Typical impedance range for a high voltage lead 10-60 Ohms
What is the current in a 2.5 volt system with a 500 $\Omega$ resistance?
Ohm’s Law

What is the current in a 2.5 volt system with a 500 Ω resistance?

\[ I = \frac{V}{R} = \frac{2.5 \text{ V}}{500 \Omega} = 0.005 \text{ A} \]

\[ 0.005 \text{ A} \times 1000 \text{ mA} = 5 \text{ mA} \]

When the impedance is 500 ohms the absolute value of the current is 2x’s the voltage.
18. A lead fracture would result in which of the following?
a. decreased battery longevity  
b. decreased conductor impedance values  
c. decreased electrode impedance values  
d. decreased current drain
Energy Formula

\[ E = V \times I \times PW \]
\[ E = \frac{V^2}{R} \times PW \]
\[ E = I^2 \times R \times PW \]

If you leave current in mA and time in Msec your answer will be in uJ
15. A patient’s stimulation threshold was 1.0 Volt & 0.2 msec pulse duration. The pacemaker is programmed to 2.0 Volt & 0.4 msec duration. Lead impedance measures 1000 Ohms. The output energy for this patient would be:
   a. 2X threshold
   b. 4X threshold
   c. 6X threshold
   d. 8X threshold
E = \frac{V^2 \times t}{R}

\begin{align*}
1^2 \times .2 &= .2 \\
1000 &= 1000
\end{align*}

\begin{align*}
2^2 \times .4 &= 1.6 \\
1000 &= 1000
\end{align*}

Doubling the voltage is 4 times the energy and doubling the PW is 2 times the energy
Lead Impedance and Energy

Case A: 2.5 V, 500 Ω, 0.5 ms
\[ E = \frac{6.25}{500 \times 0.5} \]
\[ E = 6.3 \, \mu J \]

Case B: 2.5 V, 750 Ω, 0.5 ms
\[ E = \frac{6.25}{750 \times 0.5} \]
\[ E = 4.2 \, \mu J \]

33% decrease in energy use
Energy = V x I x T

Pacemaker Pulse Widths = .1 - 1.5 ms

4.0 V x 8.0 mA x .5 ms = 20 uJ

ICD Pulse Widths = 3-15 ms range

750 V x 14,000 mA x 3 ms = 31.5 J
or 31,500,000 uJ

In pacing, charge describes the amount of electricity delivered to the myocardium during an atrial or ventricular output.

Charge (Q) is the product of pulse duration (t) in milliseconds & output current (I) in milliamperes. In pacing it is usually expressed in microcoulombs.

\[ Q = I \times T \]
Power

- Power is the rate of doing work or transmitting energy.
- Power $P = I \times V$: where $P$ is in watts, $I$ is in amperes and $V$ is in volts.
22. What is the estimated battery service life of a pacemaker with a 1.0 Amp-hour battery and a 20 microamp current drain?
   a. 4.0 years
   b. 5.0 years
   c. 5.7 years
   d. 10.0 years
1.0 Amp-hour battery and a 20 microamp current drain

Time = \( \frac{Q}{I} \)

- Battery capacity in Ah
- Current drain in amperes

\[
\text{Time} = \frac{1,000,000 \text{ uA/hr}}{20 \text{ uA}} = \frac{50,000 \text{ hr}}{8,760 \text{ hr/yr}} = 5.7 \text{ yrs}
\]
Factors Affecting Current Drain

- Lead/tissue interface
- Stimulation threshold & safety margins desired
- Quiescent current
- Impedance
- Electrode design & materials
- Pacemakers programmed settings
- % pacing
Quiescent Current

- Housekeeping – current utilized when not pacing; i.e., current used for ongoing tasks like monitoring the intrinsic rhythm & logging data. Typically in the 8-12 uA range for pacemakers

- Reducing the output from 4.0 to 2.0 V may increase the battery longevity from 4 to 6 yrs, still have housekeeping needs
## Bipolar

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Pulse Amplitude</td>
<td>4.6 Volts</td>
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<tr>
<td>Pulse Current</td>
<td>16.7 mAmperes</td>
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<tr>
<td>Pulse Energy</td>
<td>44 μJoules</td>
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<tr>
<td>Pulse Charge</td>
<td>12 μCoulombs</td>
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<tr>
<td>Lead Impedance</td>
<td>276 Ohms</td>
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## Atrial

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse Amplitude</td>
<td>2.9 Volts</td>
</tr>
<tr>
<td>Pulse Current</td>
<td>6.3 mAmperes</td>
</tr>
<tr>
<td>Pulse Energy</td>
<td>9 μJoules</td>
</tr>
<tr>
<td>Pulse Charge</td>
<td>3 μCoulombs</td>
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<tr>
<td>Lead Impedance</td>
<td>462 Ohms</td>
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## Unipolar

<table>
<thead>
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<th>Value</th>
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</thead>
<tbody>
<tr>
<td>Pulse Amplitude</td>
<td>4.8 Volts</td>
</tr>
<tr>
<td>Pulse Current</td>
<td>10.7 mAmperes</td>
</tr>
<tr>
<td>Pulse Energy</td>
<td>36 μJoules</td>
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<tr>
<td>Pulse Charge</td>
<td>9 μCoulombs</td>
</tr>
<tr>
<td>Lead Impedance</td>
<td>444 Ohms</td>
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## Atrial

<table>
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</thead>
<tbody>
<tr>
<td>Pulse Amplitude</td>
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</tr>
<tr>
<td>Pulse Current</td>
<td>5.9 mAmperes</td>
</tr>
<tr>
<td>Pulse Energy</td>
<td>8 μJoules</td>
</tr>
<tr>
<td>Pulse Charge</td>
<td>3 μCoulombs</td>
</tr>
<tr>
<td>Lead Impedance</td>
<td>582 Ohms</td>
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## Battery Data

<table>
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<tr>
<th>Parameter</th>
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</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>2.71 Volts</td>
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<tr>
<td>Current</td>
<td>39 μAmperes</td>
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<tr>
<td>Impedance</td>
<td>&lt;1 Kohms</td>
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</table>

## Battery Data

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<tr>
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<tbody>
<tr>
<td>Voltage</td>
<td>2.71 Volts</td>
</tr>
<tr>
<td>Current</td>
<td>32 μAmperes</td>
</tr>
<tr>
<td>Impedance</td>
<td>&lt;1 Kohms</td>
</tr>
</tbody>
</table>
## Fracture / Connector / Uni Leads

<table>
<thead>
<tr>
<th></th>
<th>Atrial Lead</th>
<th>Ventricular Lead</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude</td>
<td>2.73 V</td>
<td>2.73 V</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>0.31 ms</td>
<td>0.31 ms</td>
</tr>
<tr>
<td>Output Energy</td>
<td>0.04 µJ</td>
<td>0.10 µJ</td>
</tr>
<tr>
<td>Measured Current</td>
<td>0.05 mA</td>
<td>0.12 mA</td>
</tr>
<tr>
<td>Measured Impedance</td>
<td>&gt; 9,999 ohms</td>
<td>&gt; 9,999 ohms</td>
</tr>
<tr>
<td>Pace Polarity</td>
<td>Bipolar</td>
<td>Bipolar</td>
</tr>
</tbody>
</table>
Causes of High & Low Impedance

- **High Impedance**
  - Conductor Fracture, Loose Connector or Unipolar leads programmed to Bipolar

- **Low Impedance**
  - Insulation degradation, Y-adaptor or parallel pathways, loose connection maintaining contact with body fluids

<table>
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## Measured Data

<table>
<thead>
<tr>
<th></th>
<th>Atrial</th>
<th>Ventricular</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnet Rate</td>
<td></td>
<td>97.2 ppm</td>
</tr>
<tr>
<td><strong>Pulse Amplitude</strong></td>
<td>2.8 V</td>
<td>2.3 V</td>
</tr>
<tr>
<td><strong>Pulse Current</strong></td>
<td>4.9 mA</td>
<td>3.9 mA</td>
</tr>
<tr>
<td><strong>Pulse Energy</strong></td>
<td>5.8 μJ</td>
<td>4.5 μJ</td>
</tr>
<tr>
<td><strong>Pulse Charge</strong></td>
<td>2 μC</td>
<td>2 μC</td>
</tr>
<tr>
<td><strong>Lead Impedance</strong></td>
<td>573 Ω</td>
<td>596 Ω</td>
</tr>
</tbody>
</table>

### Battery Data

(W.G. 9438 - nominal 0.95 Ah)

<p>| | |</p>
<table>
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<tbody>
<tr>
<td><strong>Voltage</strong></td>
<td>2.73 V</td>
</tr>
<tr>
<td><strong>Current</strong></td>
<td>12 μA</td>
</tr>
<tr>
<td><strong>Impedance</strong></td>
<td>2.5 kΩ</td>
</tr>
<tr>
<td>Estimated Remaining Longevity</td>
<td>3 years</td>
</tr>
</tbody>
</table>

If you could only pick 3 values on which to base your device evaluation; which 3 would you pick?
Measured Data

If you could only pick 3 values on which to base your device evaluation; which 3 would you pick?

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<td>4.5 μJ</td>
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<td>596 Ω</td>
</tr>
</tbody>
</table>

Battery Data

(W.G. 9438 - nominal 0.95 Ah)

Voltage: 2.73 V
Current: 12 μA
Impedance: 2.5 kΩ
Estimated Remaining Longevity: 3 years
Stimulation Threshold

- The minimal amount of electrical stimulation that consistently produces a cardiac depolarization. The threshold can be expressed in terms of amplitude (milliamperes or volts), pulse duration (msec), charge (microcoulombs), or energy (microjoules).
Strength Duration Curve

- A graphic representation of the pulse amplitude, in voltage or current, required to produce an action potential in the cells. The curve is plotted as a function of pulse duration and can be defined by 2 points; the Rheobase and the Chronaxie. As the pulse duration increases, the voltage requirements decline (to a point).
The value derived from a strength-duration curve that indicates the minimum output that will stimulate the myocardium irrespective of the pulse duration. The curve typically levels out around a pulse duration of 1 msec.
Chronaxie

- The pulse duration value that is twice the rheobase.
26. The term **virtual electrode** or fibrous capsule surrounding the electrode:
   a. is a normal foreign body reaction
   b. is an unexcitable capsule of tissue
   c. decreases the current density at the lead tissue interface
   d. all of the above
Virtual Electrode

- is a normal foreign body reaction which results from acute injury to the cell membrane
- collagen is formed resulting in an unexcitable capsule of tissue which decreases the current density at the lead tissue interface
17. Which of the above 3 month stimulation threshold graphs would be most characteristic of steroid eluting tined atrial lead?

a. A  

b. B  

c. C  

d. D
Electrode Threshold Characteristics

- Polished platinum
- Porous platinum
- Activated carbon
- Steroid eluting tined lead

Pulse width (ms) vs Implant time (weeks)
The difference noted in thresholds when decrementing until loss of capture versus going from sub-threshold to capture is known as?

a. latency
b. Wedensky effect
c. intermittent threshold
d. polarization
Wedensky Effect

- Also called capture hysteresis
- The difference noted in thresholds when decrementing until loss of capture versus going from sub-threshold to capture
- Ellenbogen suggests the phenomena is probably explained by varying rates during gain or loss of capture and that effects may be greatest at narrow pulse durations

Ellenbogen & Woods. Cardiac Pacing & ICD’s, p 53
Output Programming

- Rule of thumb
- Double Voltage
- Triple PW
Doubling Voltage

- Chronic threshold
  0.5ms & 2.5V so voltage was doubled
- Tripling PW would give an inadequate safety margin
If the threshold was determined to be at point C in the above figure; which of the following would result in an efficient and appropriate safety margin?

- a. Double voltage
- b. Triple the pulse width
- c. Triple the voltage
- d. Double the pulse width
Voltage Strength Duration Curve

- Steep Region
- "Knee" Region
- Flat Region

Best programming
## Output Settings & Longevity

<table>
<thead>
<tr>
<th>Battery Status</th>
<th>OK</th>
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</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>2.74 V</td>
</tr>
<tr>
<td>Current</td>
<td>31.73 µA</td>
</tr>
<tr>
<td>Impedance</td>
<td>575 ohms</td>
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</tbody>
</table>

Estimated at
- Minimum: 31 months
- Maximum: 36 months

Based on 100% Pacing

<table>
<thead>
<tr>
<th>Lead Status</th>
<th>Collected: 2:10:15 PM</th>
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<tbody>
<tr>
<td>Atrial Lead</td>
<td>Ventricular Lead</td>
</tr>
<tr>
<td>Amplitude</td>
<td>4.43 V</td>
</tr>
<tr>
<td>Pulse Width</td>
<td>0.46 ms</td>
</tr>
<tr>
<td>Output Energy</td>
<td>12.58 µJ</td>
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<tr>
<td>Measured Current</td>
<td>6.65 mA</td>
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<tr>
<td>Measured Impedance</td>
<td>620 ohms</td>
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<tr>
<td>Pace Polarity</td>
<td>Bipolar</td>
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<tr>
<th>Battery Status</th>
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</thead>
<tbody>
<tr>
<td>Voltage</td>
<td>2.76 V</td>
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<tr>
<td>Current</td>
<td>20.49 µA</td>
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<tr>
<td>Impedance</td>
<td>602 ohms</td>
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Estimated at
- Minimum: 40 months
- Maximum: 59 months

Based on 100% Pacing

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<tbody>
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<tr>
<td>Amplitude</td>
<td>2.67 V</td>
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<td>Pulse Width</td>
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<td>Output Energy</td>
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<td>Measured Current</td>
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<td>Measured Impedance</td>
<td>607 ohms</td>
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<tr>
<td>Pace Polarity</td>
<td>Bipolar</td>
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</tbody>
</table>
Antiarrhythmics That Increase Pacing Thresholds

- **Class IA**
  - Quinidine
  - Disopyramide
  - Procainamide

- **Class IC**
  - Flecainide – notorious
  - Propafenone

- **Class III**
  - Amiodorone
  - *Sotalol- decreases ICD thresholds
  - Prapafenone
Electrolyte Abnormalities That Increase Pacing Thresholds

- Acidosis
- Alkalosis
- Hyperkalemia
- Hypocalcemia
- Hyperglycemia
- Hypercarbia
- Hypoxemia
Temporal Conditions That Increase Pacing Thresholds

- Sleeping
- Acute viral illness
- Eating
- Lead maturation
- Excessive alcohol – increases defibrillation thresholds

Papaioannou GI, et al. PACE 2002; 25:1144
Factors That Decrease Pacing Thresholds

- Corticosteroids - dexamethasone
- Exercise
- Catecholamines
- Hypocapnia
- Sympathomimetic agents - Isuprel, epinephrine, ephedrine, atropine
- Hyperoxia
Thank you for your kind attention
What’s the point?
Ohm’s Law

What would be the calculated voltage in a 10 mA system with 500 Ω of impedance?
Ohm’s Law

What would be the calculated voltage in a 10 mA system with 500 Ω of impedance?

\[ V = I \times R \]

\[ 10 \text{ mA} \times 500 \text{ Ω} = 5000 \]

\[ 5000 \text{ mV} \times \frac{1 \text{ V}}{1000 \text{ mV}} = 5 \text{ V} \]
- Chronic threshold 2.5V & .2ms PW, PW programmed to .6ms providing a 2.1x safety margin.
Ohm’s Law tattoo
Polarization

Capacitance effect: positively charged ions resist ion flow

Electrode

Electrode-Tissue Interface
Polarization/Afterpotential

- Voltage that persists for a time after a paced impulse
- Could cause oversensing
- Polarization can represent 30-40% of total pacing impedance
Garden Hose Analogy

Normal Resistance = normal current flow

Low Resistance = high current flow

High Resistance = low current flow
**Terminology**

- Current: flow of electrons through a circuit mA
Voltage: Electromotive push

Provided by
The battery

Pacemaker

Conductor Wire

Heart
V = IR  \quad \text{Ohm’s Law}

V = 5.0 \text{ mA} \times 0.500 \text{ Kohms}

V = 2.5 \text{ Volts}
Ohm’s Law

What would be the impedance of a 2.5 volt system with a 10 mA current drain?

\[
R = \frac{V}{I} = \frac{2.5 \text{ V}}{10 \text{ mA}} = \frac{2.5 \text{ V}}{0.01 \text{ A}} = 250 \Omega
\]

\[
10 \text{ mA} \times \frac{1 \text{ A}}{1000 \text{ mA}} = 0.01 \text{ A}
\]
Energy: Voltage x Current x Time

\[ E = V \times I \times t \]

Current in mA
Time in ms
Unit = Joule (J)
ENERGY & LONGEVITY

\[ E = V \times I \times T \] or \[ E = \frac{V^2}{R \times T} \]

Case A: 2.5 V, 750 \( \Omega \), 0.5 ms

\[ E = \frac{6.25}{750 \times 0.5} \]

\[ E = 4.2 \ \mu \text{J} \]

Case B: 5.0 V, 750 \( \Omega \), 0.5 ms

\[ E = \frac{25}{750 \times 0.5} \]

\[ E = 16.7 \ \mu \text{J} \]

Four times the energy demand
46. Match the units: watt-second
   a. energy
   b. power
   c. capacitance
   d. current drain
Strength Duration

RHEOBASE AND CHRONAXIE TIME

RHEOBASE x 2

RHEOBASE

CHRONAXIE TIME

AMPLITUDE
Strength Duration

RHEOBASE AND CHRONAXIE TIME

AMPLITUDE

RHEOBASE

CHRONAXIE TIME

RHEOBASE x 2
Strength Duration

RHEOBASE AND CHRONAXIE TIME

AMPLITUDE

RHEOBASE x 2

RHEOBASE

CHRONAXIE TIME
- joule: unit of energy or work
- henry: unit of inductance (induced by a magnetic field)
- coulomb: unit of charge
34. The rate at which work is done is is:
   a. joule    unit of energy or work
   b. farad    basic unit of capacitance
   c. power    unit of charge
   d. coulomb  unit of charge
62. In the above figure line B represents the:
   a. Chronaxie
   b. Pulse width threshold
   c. Knee of the curve
   d. Rheobase
Fundamentals of Electronics

Low Resistance = high current flow

High Resistance = low current flow
Fundamentals of Electronics

- System Impedance
  - Cathode Electrode Impedance
  - Anode Electrode Impedance
  - Polarization Impedance
  - Tissue Impedance

- Typical range for pacing lead impedance: 300 to over 1200 Ohms

- Typical impedance range for a high voltage lead 10-60 Ohms
Energy, Power, Watts & Current Drain

- Energy: the ability to do work; for batteries usually expressed in watt-hours
- Energy density: the energy content of a battery or capacitor based on volume or mass. For a battery is expressed in units of watt-hrs per cubic-centimeter or watt-hrs per gram
- Power: the rate of doing work or transmitting energy, a product of voltage & current usually expressed in watts
- Watt: international unit of electrical power, watts are equivalent to joules per second
- Watt-hour: the amount of energy at a rate of 1 watt per hour, 1 joule = 1watt delivered for 1 second, 1 watt-hour = 3,600 joules
- Current drain: the average amount of current drawn from a battery by the external load; typically pacemakers draw from 10 – 30 microamperes

Current $I = \frac{V}{R}$

Pacemaker

$4.0 \text{ V} = (I) \ 500 \text{ ohms}$

$4.0 \text{ V/.500 Kohms} = 8.0 \text{ mA}$

ICD

$600-830 \text{ V i,e. } 750 \text{ V} = (I) \ 50 \text{ ohms}$

$750 \text{ V/.050 Kohms} = 15,000 \text{ mA}$
Pacemaker Longevity Factors

- Battery Capacity
- Rate of Drain
- Circuit Efficiency
- Pacing Rate
- Programmed output & Pulse Duration
- % of time pacing
45. The horizontal asymptote of a strength duration curve defines which of the following:
   a. charge
   b. pulse width threshold
   c. rheobase
   d. chronaxie
Strength Duration Curves

- Volts in Volts
- Energy in Microjoules
- Current in Milliamperes
- Charge in Microcoulombs

Charge $\frac{\mu C}{\mu J}$

Energy $\frac{\mu J}{\mu C}$

Volts
Current

Pulse Duration (msec.)
ESTIMATED LONGEVITY

Assumes 100% pacing in DDDR @ 70 ppm, 500 Ω