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

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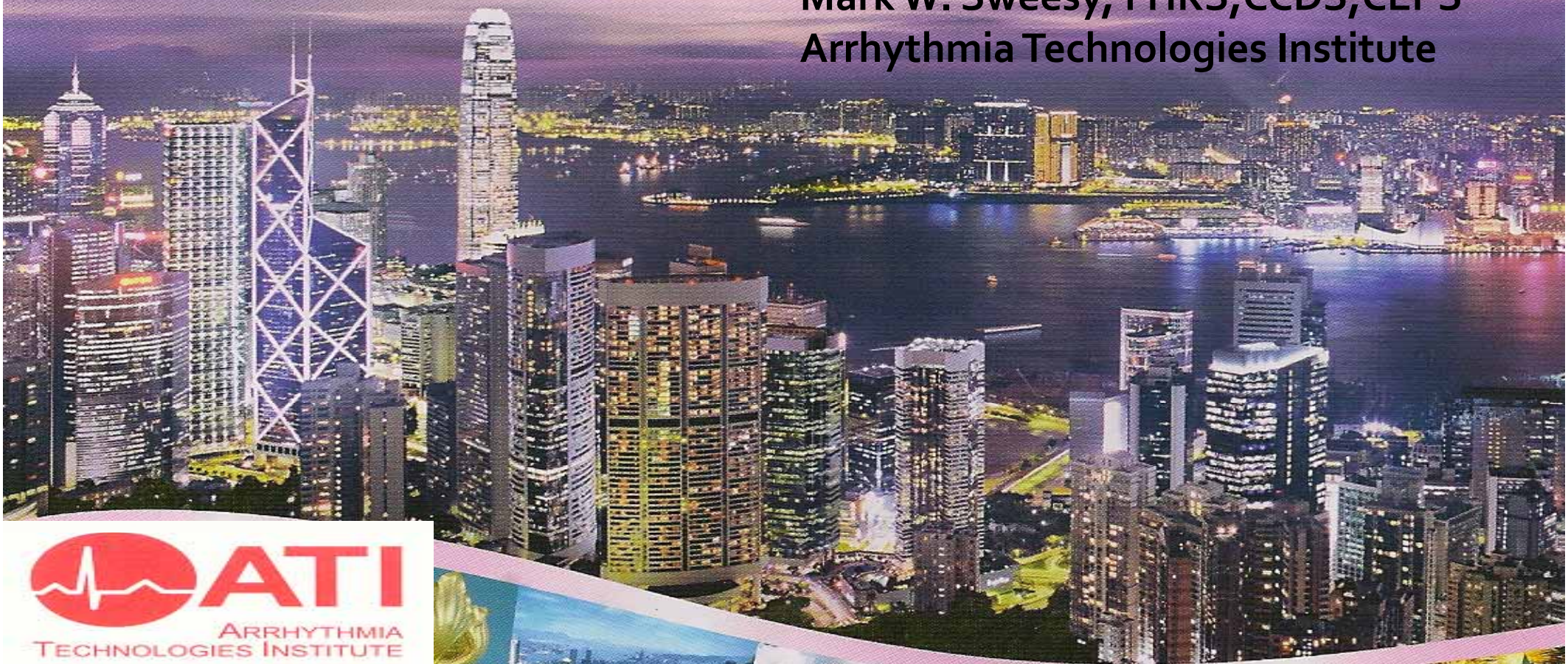


ATI
Arrhythmia Technologies Institute

Outline

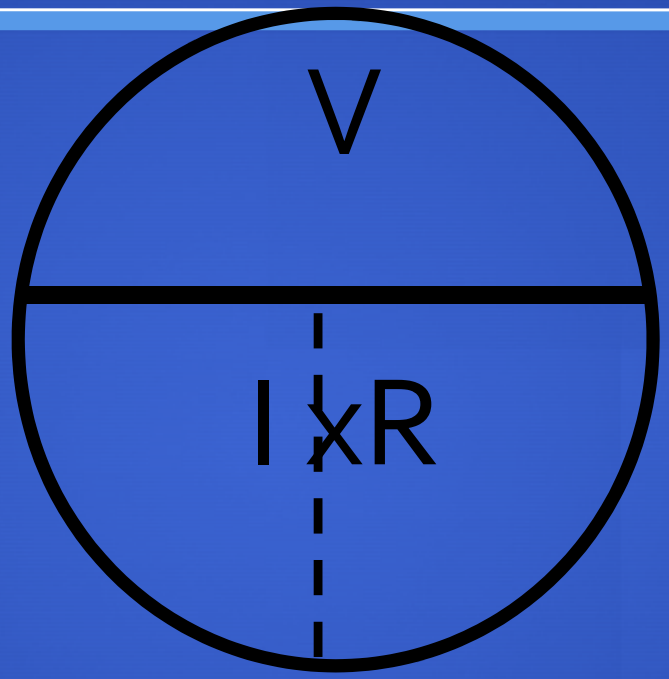
- Ohm's Law
  - Voltage, current and resistance (impedance)
  - Energy and power
  - Clinical relevance
- Strength duration curve
  - Rheobase
  - Chronaxie
  - Clinical relevance

Ohm's Law

V = I x R

I = V / R

R = V / I



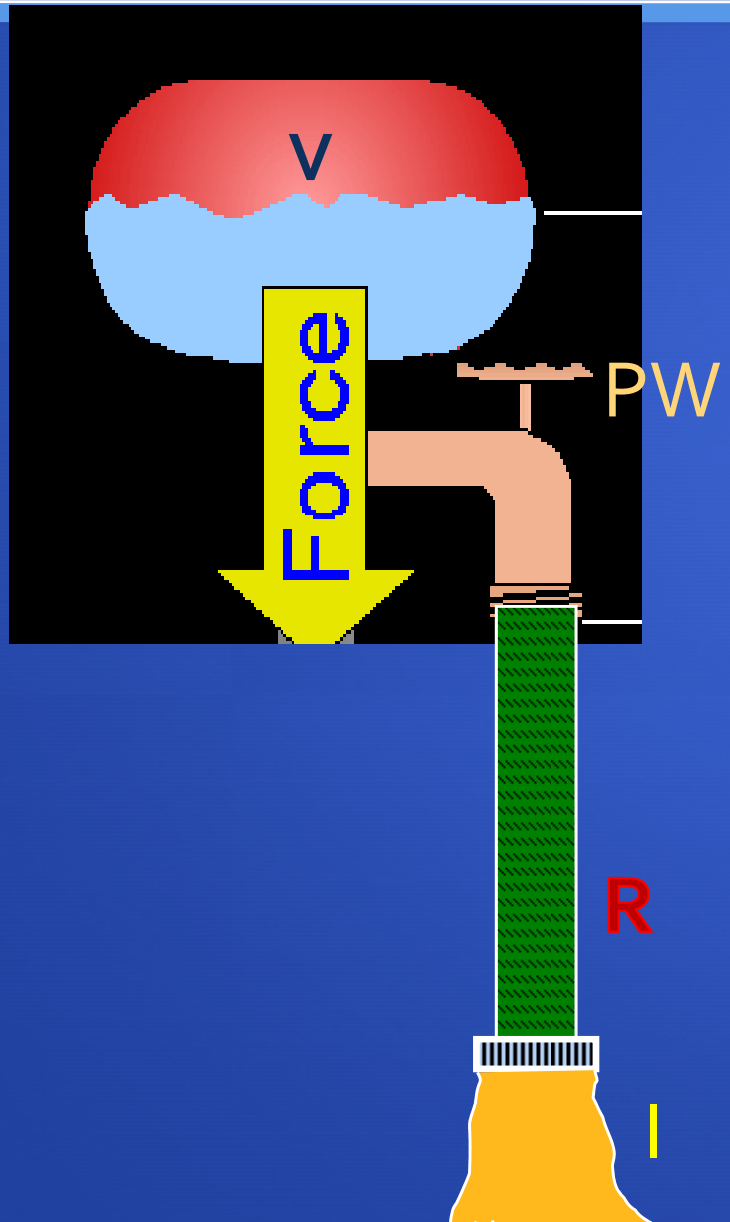
The equation uses current in the form of Amps
In pacing current is expressed in mA

Fundamentals of Electronics

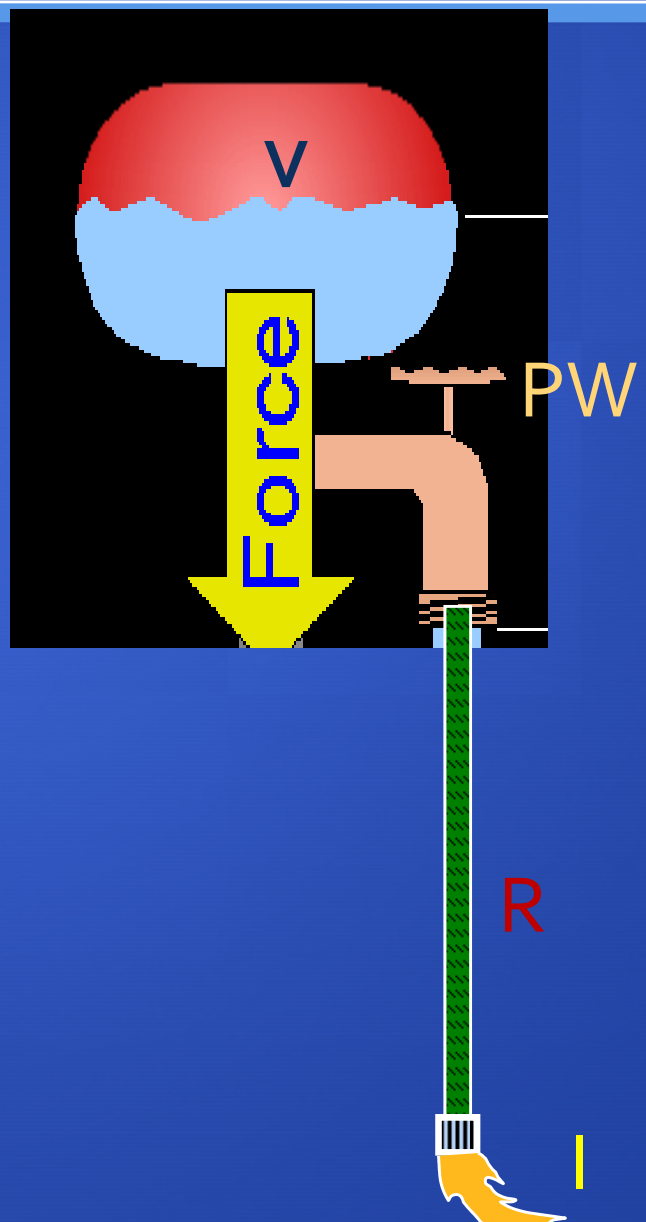
- Voltage (V): force moving the current: electromotive push
- Current (I): flow of electrons through a circuit mA
- Resistance (R) / Impedance: opposition to current flow: Unit of measure: Ohm (Ω)

Fundamentals of Electronics

Low Resistance = high current flow



High Resistance = low current flow



Ohm's Law: Pacers vsICD'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

Ohm's Law

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

Ohm's Law

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

$$I = \frac{V}{R} = \frac{2.5\,V}{500\,\Omega} = .005\ A$$

$$.005\ A \times \frac{1000\ mA}{1\ A} = 5\ mA$$

When the impedance is 500 ohms the absolute value of the current is 2x's the voltage

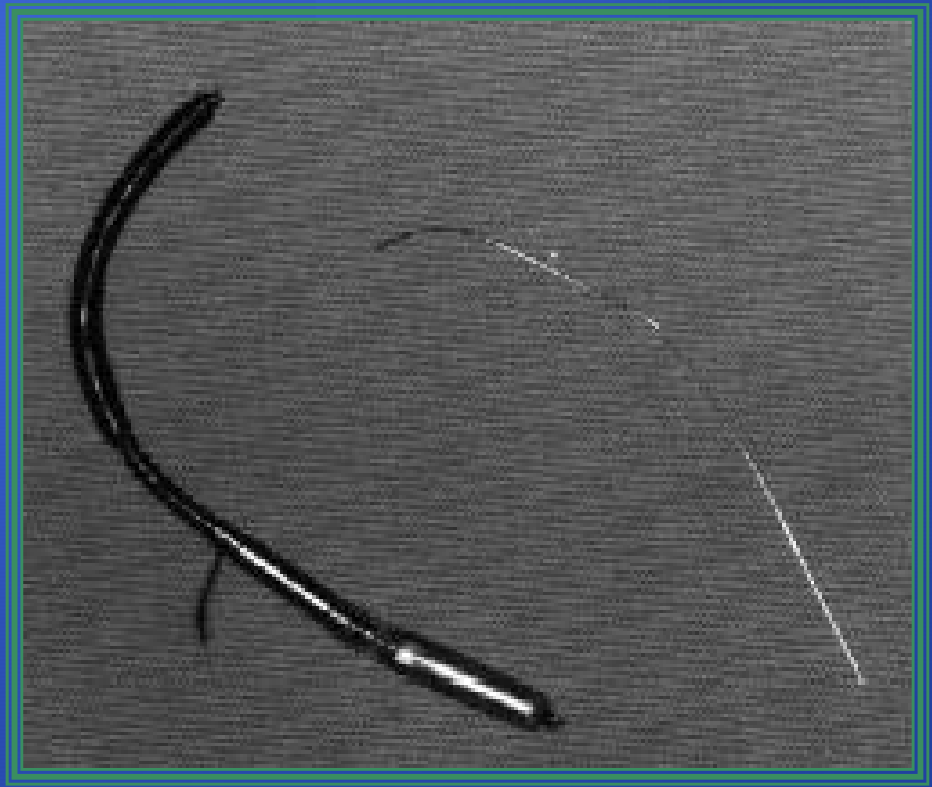
18. A lead fracture would result in which of the following?

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

$$E = \frac{V^2 \times t}{R}$$

$$\frac{1^2 \times .2}{1000} = \mathbf{.2}$$

$$\frac{2^2 \times .4}{1000} = \mathbf{1.6}$$

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

$E = 6.25 / 500 \times 0.5$

$E = 6.3\ \mu J$

Case B: 2.5 V, 750 Ω, 0.5 ms

$E = 6.25 / 750 \times 0.5$

$E = 4.2\ \mu J$

33% decrease in energy use

Energy = V x I x T

Pacemaker Pulse Widths= .1 -1.5 ms

4.0 V x 8.0 mAx .5 ms = 20 uJ

ICD Pulse Widths = 3-15 ms range[1]

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

1. Thammanomai A, et al. Heart Rhythm 2006; 3:1053-1059

Charge

- 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

$$\text{Time} = \frac{Q}{I} \quad \begin{matrix} \text{battery capacity in Ah} \\ \text{current drain in amperes} \end{matrix}$$

$$\text{Time} = \frac{1{,}000{,}000 \text{ uA/hr}}{20 \text{ uA}} = \frac{50{,}000 \text{ hr}}{8{,}760 \text{ hr/yr}} = 5.7 \text{ yrs}$$

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

entricular:

Pulse Amplitude	4.6	Volts
Pulse Current	16.7	mAmperes
Pulse Energy	44	µJoules
Pulse Charge	12	µCoulombs
Lead Impedance	276	Ohms

trial:

Pulse Amplitude	2.9	Volts
Pulse Current	6.3	mAmperes
Pulse Energy	9	µJoules
Pulse Charge	3	µCoulombs
Lead Impedance	462	Ohms

attery Data: (W.G. 8708 - NOM. 1.2 AHR)

Voltage	2.71	Volts
Current	39	µAmperes
Impedance	<1	KOhms

Unipolar

Ventricular:

Pulse Amplitude	4.8	Volts
Pulse Current	10.7	mAmperes
Pulse Energy	36	µJoules
Pulse Charge	9	µCoulomb
Lead Impedance	444	Ohms

Atrial:

Pulse Amplitude	2.9	Volts
Pulse Current	5.9	mAmperes
Pulse Energy	8	µJoules
Pulse Charge	3	µCoulomb
Lead Impedance	502	Ohms

Battery Data: (W.G. 8708 - NOM. 1.2 AHR)

Voltage	2.71	Volts
Current	32	µAmperes
Impedance	<1	KOhms

Fracture / Connector / Uni Leads

	Atrial Lead	Ventricular Lead
Amplitude	2.73 V	2.73 V
Pulse Width	0.31 ms	0.31 ms
Output Energy	0.04 µJ	0.10 µJ
Measured Current	0.05 mA	0.12 mA
Measured Impedance	> 9,999 ohms	> 9,999 ohms
Pace Polarity	Bipolar	Bipolar

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 maintainingcontact with body fluids[1]

	Atrial Lead	Ventricular Lead
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1. In Ellenbogen K, et al. Clinical Cardiac Pacing, Defibrillation & CRT. 2007; pp 834

Measured Data

Measured Data

Magnet Rate	97.2	ppm

	Atrial		Ventricular	
Pulse Amplitude	2.8	V	2.3	V
Pulse Current	4.9	mA	3.9	mA
Pulse Energy	5.8	μJ	4.5	μJ
Pulse Charge	2	μC	2	μC
Lead Impedance	573	Ω	596	Ω

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

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

Measured Data

Measured Data

Magnet Rate			97.2	ppm
	Atrial		Ventricular	
Pulse Amplitude	2.8	V	2.3	V
Pulse Current	4.9	mA	3.9	mA
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Current			12	μA
Impedance			2.5	kΩ
Estimated Remaining Longevity			3	years

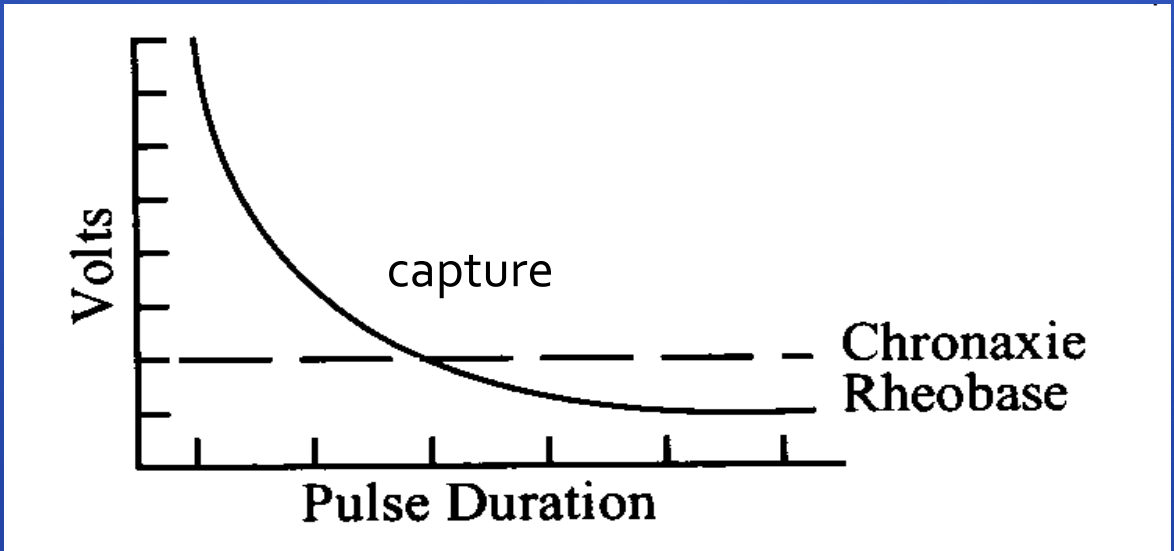
If you could only pick 3 values on which to base your device evaluation; which 3 would you pick?

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).

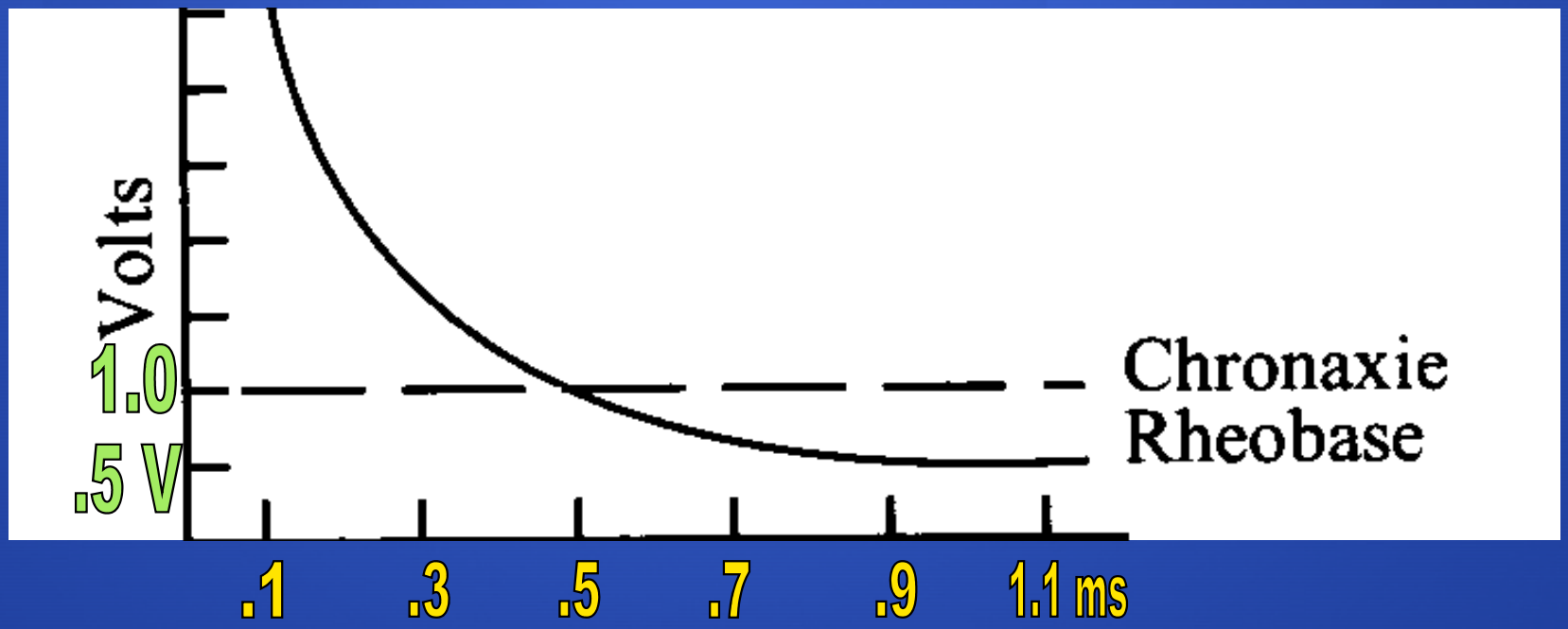
Strength Duration Curve

- 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).



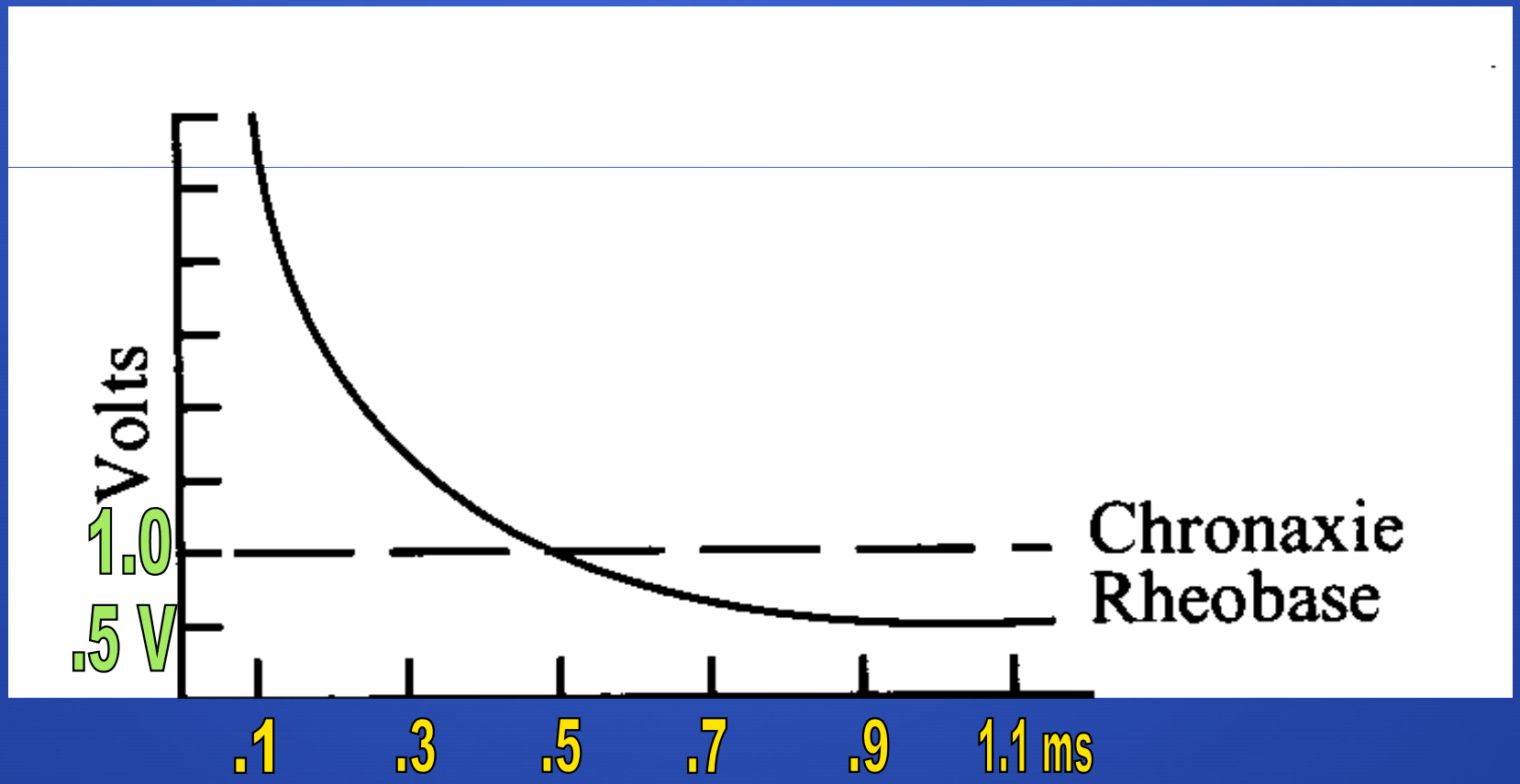
Rheobase

- 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.



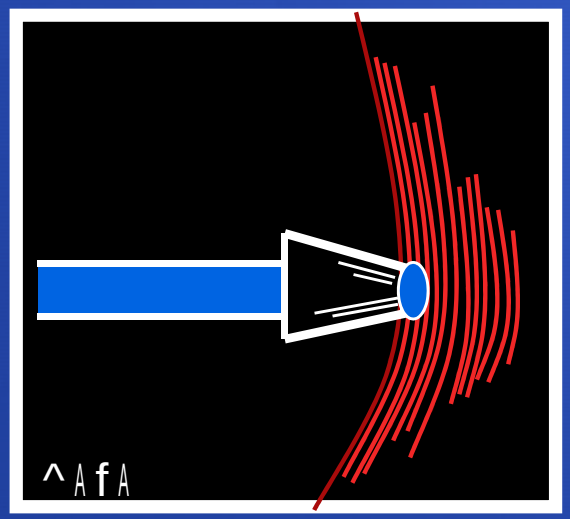
26. The term **virtual electrode** or fibrous capsule surrounding the electrode:

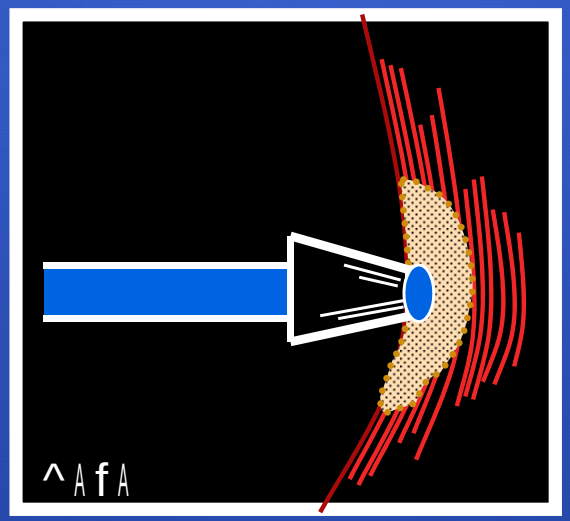
a. is a normal foreign body reaction

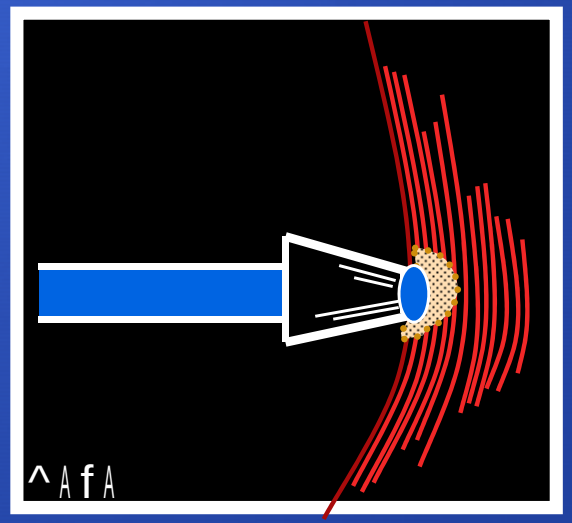
b. is an unexcitable capsule of tissue

c. decreases the current density at the lead tissue interface

d. all of the above

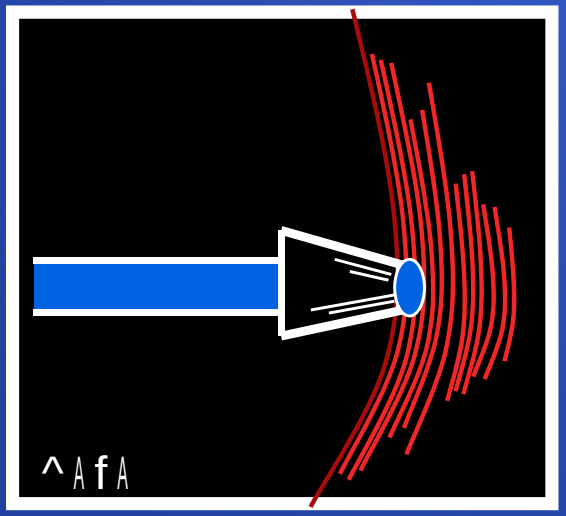


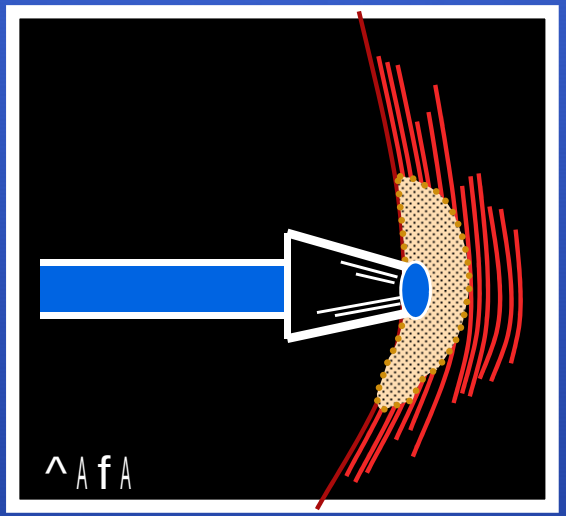


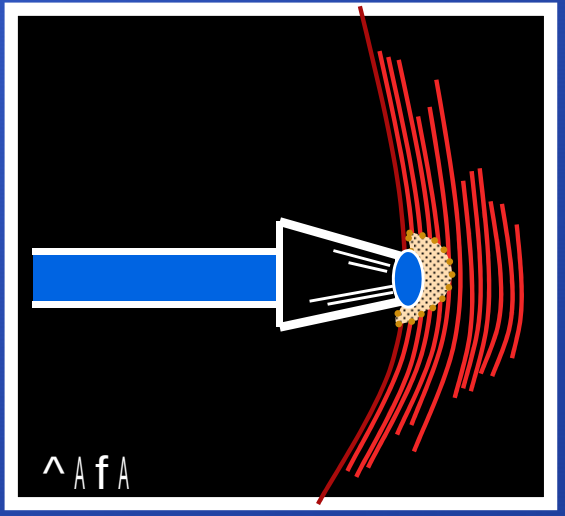


Virtual Electrode

- is a normal foreign body reaction which results from acute injury to the cell membrane
- collagen is formed resulting in anunexcitable capsule of tissue which decreases the current density at the lead tissue interface

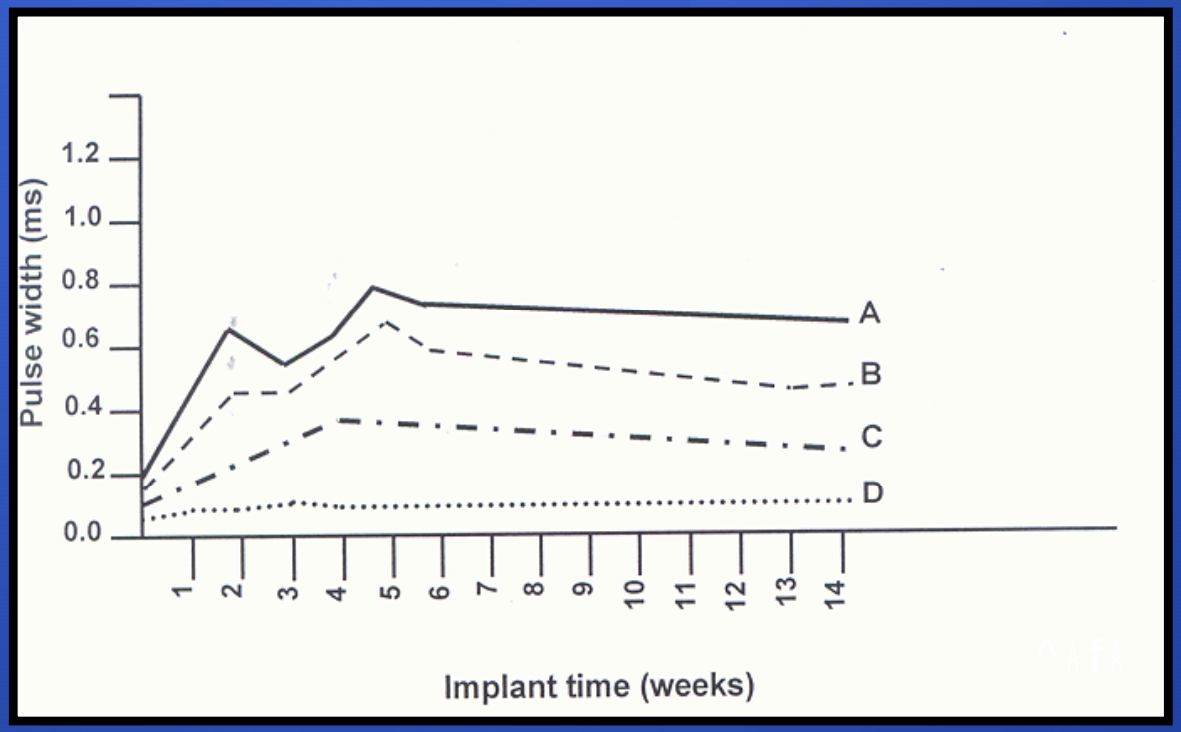




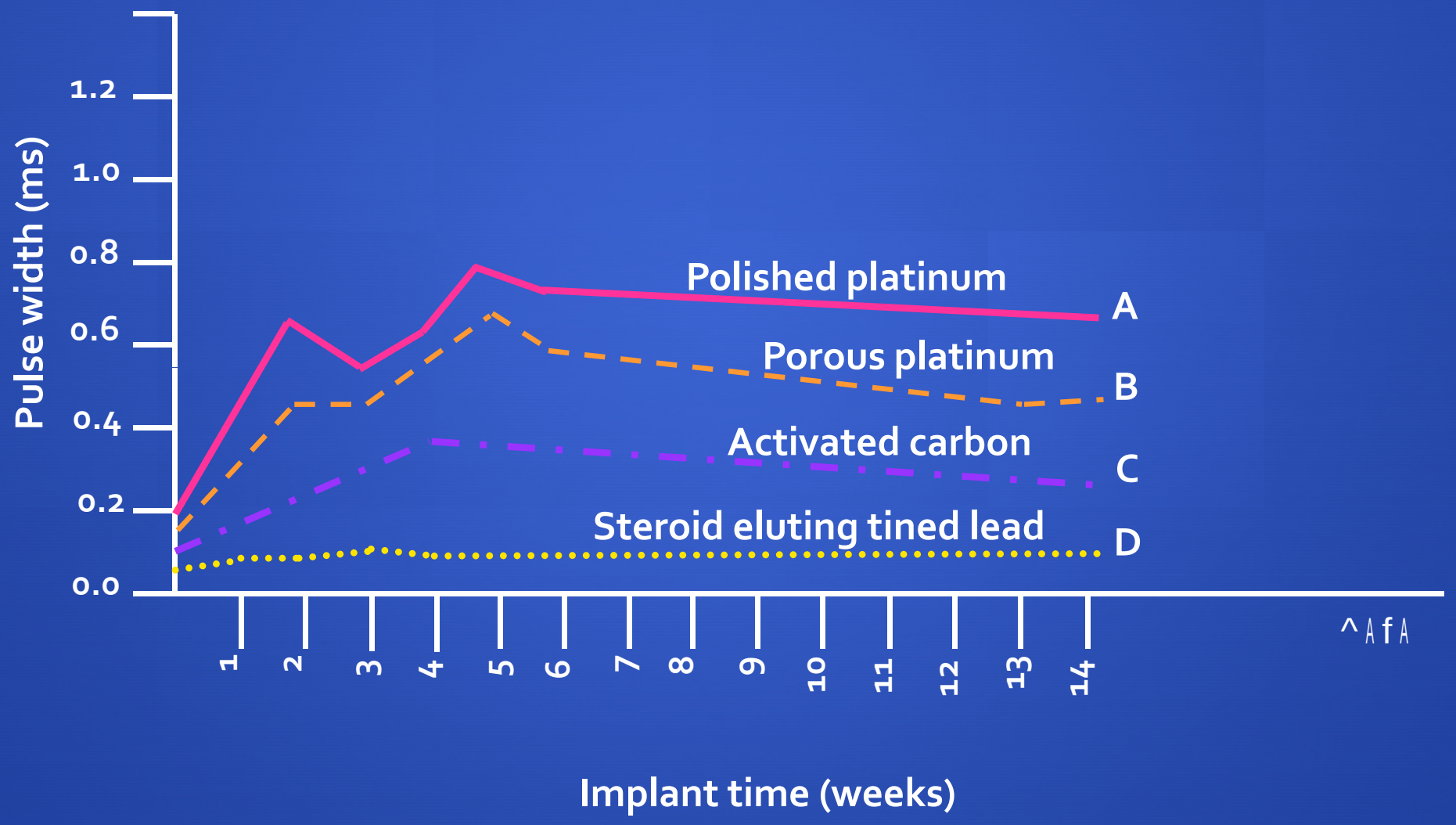


17. Which of the above 3 month stimulation threshold graphs would be most characteristic of steroid eluting tined atrial lead?

a. A
b. B
c. C
d. D



Electrode Threshold Characteristics



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

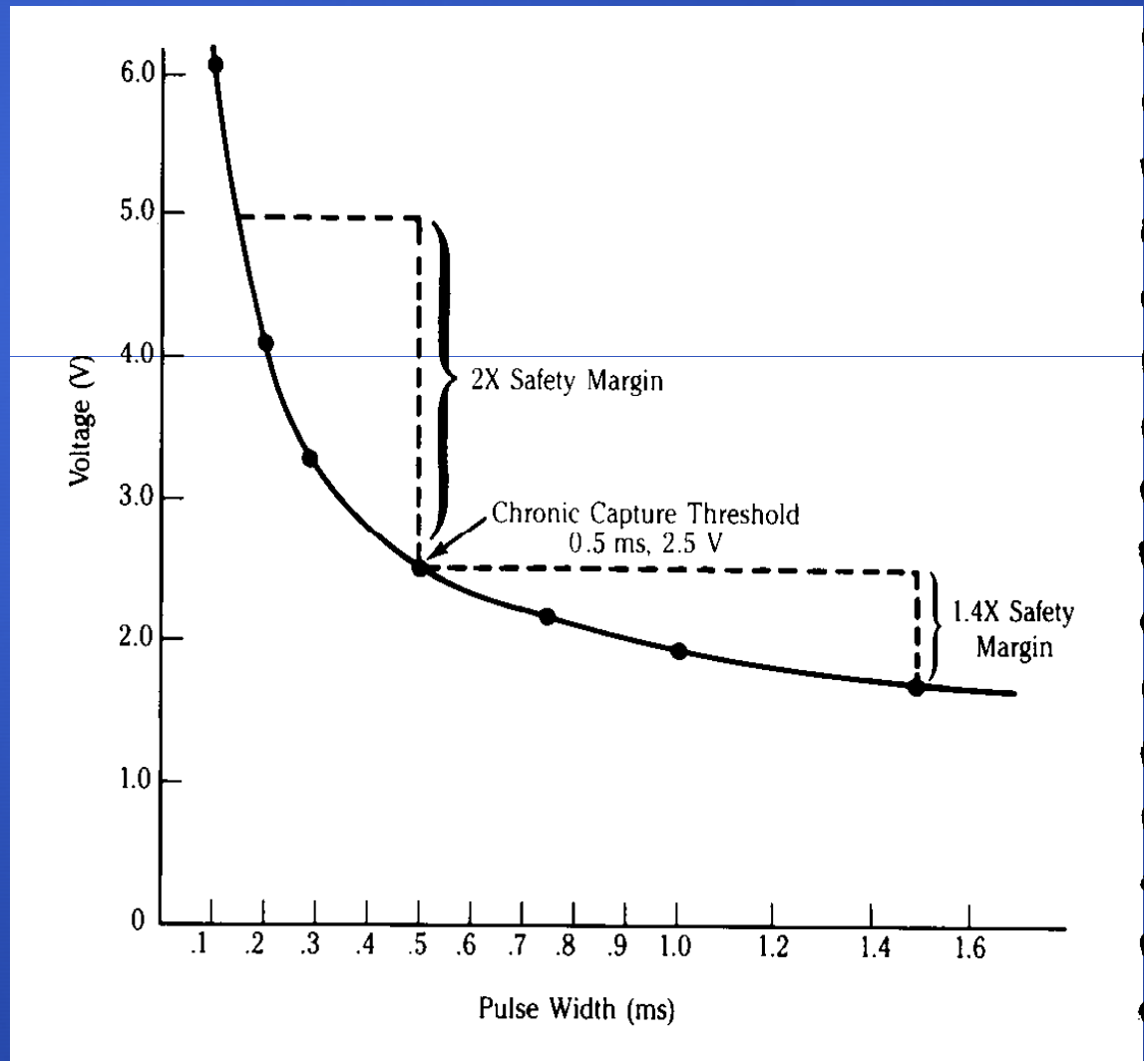
- Rule of thumb
- Double Voltage
- Triple PW

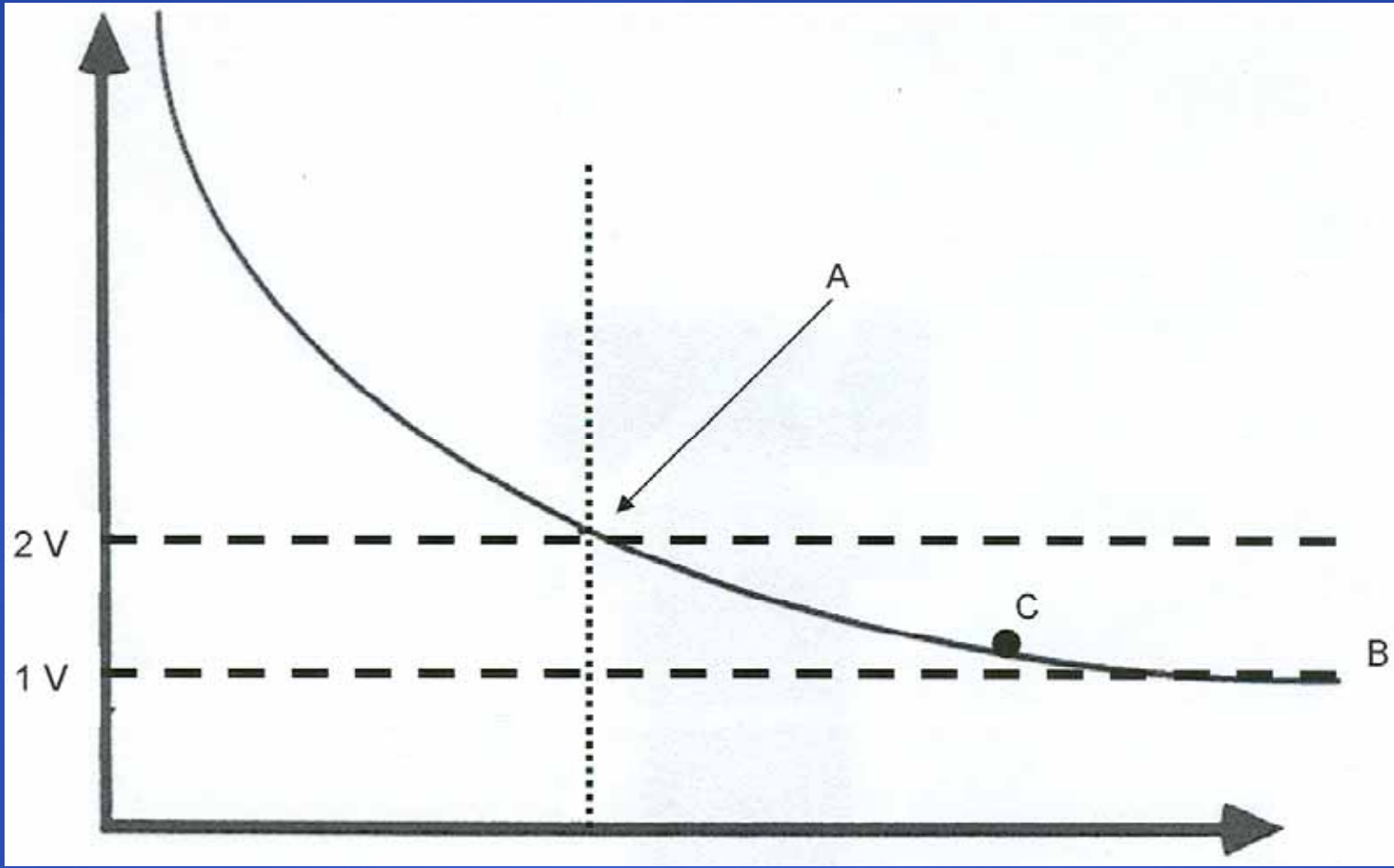
Doubling Voltage

- Chronic threshold

.5ms & 2.5V so voltage was doubled

- Tripling PW would give an inadequate safety margin

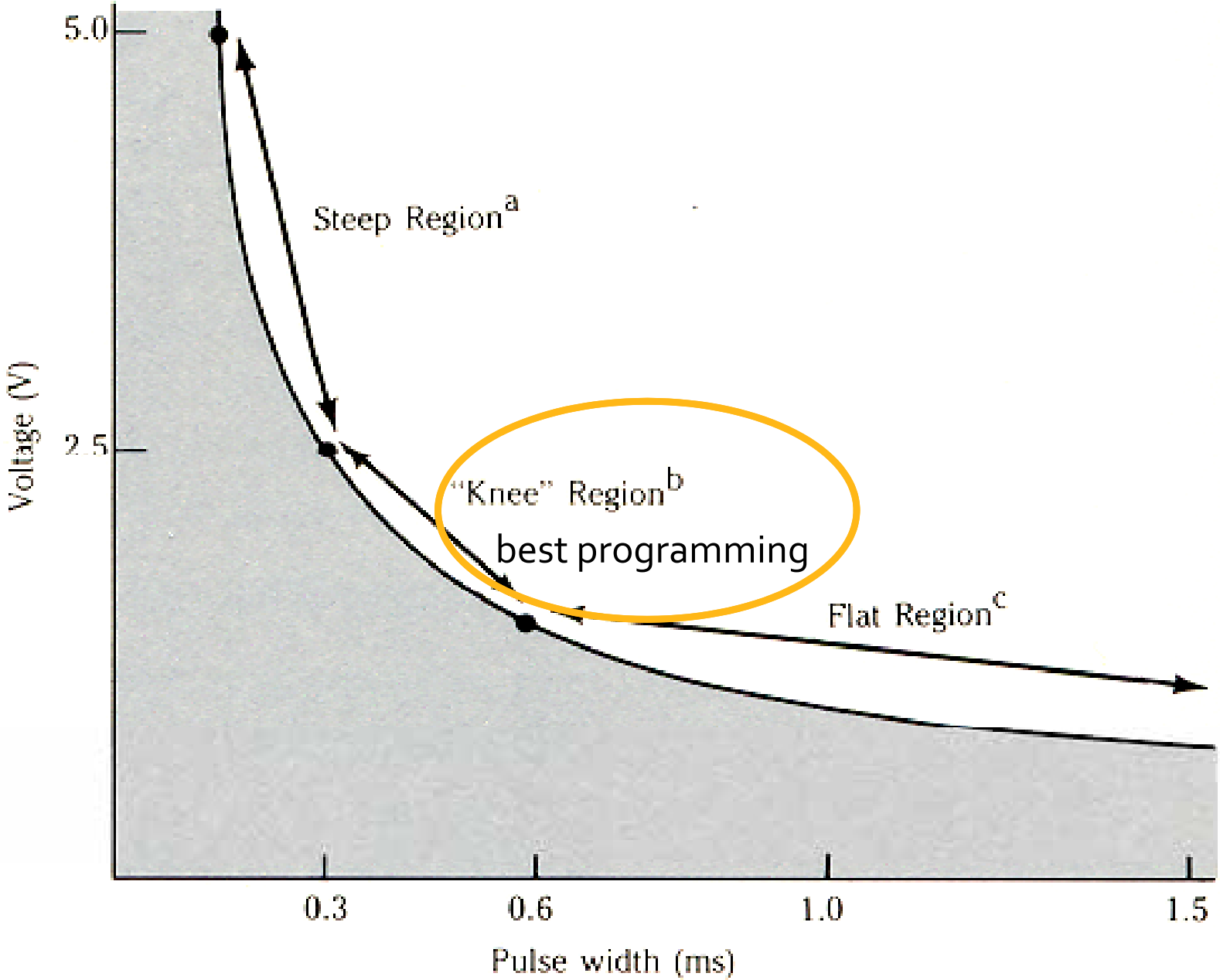




63 . If the threshold was determined to be at point C in the above figure; which of the following would result in an efficient and appropriate safety margin?

a. Double voltage
b. Triple the pulse width
c. Triple the voltage
d. Double the pulse width

Voltage Strength Duration Curve



Output Settings & Longevity

Battery Status	OK
Voltage	2.74 V
Current	31.73 µA
Impedance	575 ohms
Estimated at	31 months
Minimum	25 months
Maximum	36 months
Based on 100% Pacing	

Lead Status Collected: 2:10:15 PM

	Atrial Lead	Ventricular Lead
Amplitude	4.43 V	4.41 V
Pulse Width	0.46 ms	0.46 ms
Output Energy	12.58 µJ	13.64 µJ
Measured Current	6.65 mA	7.29 mA
Measured Impedance	620 ohms	560 ohms
Pace Polarity	Bipolar	Bipolar

Battery Status	OK
Voltage	2.76 V
Current	20.49 µA
Impedance	602 ohms
Estimated at	49 months
Minimum	40 months
Maximum	59 months
Based on 100% Pacing	

Lead Status Collected: 2:14:03 PM

	Atrial Lead	Ventricular Lead
Amplitude	2.67 V	2.66 V
Pulse Width	0.31 ms	0.31 ms
Output Energy	3.26 µJ	3.56 µJ
Measured Current	4.20 mA	4.61 mA
Measured Impedance	607 ohms	547 ohms
Pace Polarity	Bipolar	Bipolar

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[1]

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?

$V = I \times R$

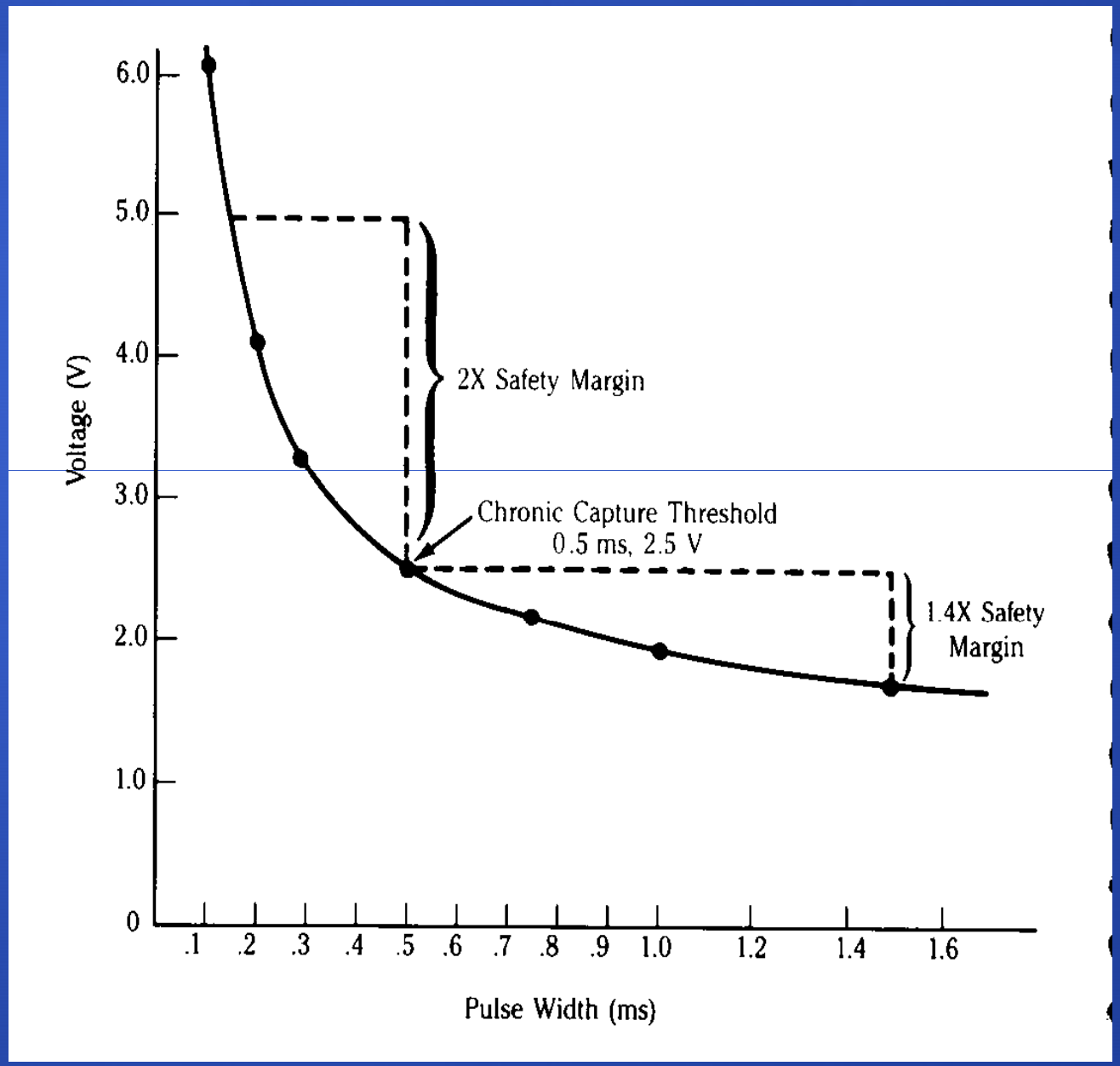
$10\ mA \times 500\ \Omega = 5000$

$$5000\ mV \times \frac{1\ V}{1000\ mV}$$

$5V$

Tripling Pulse Width

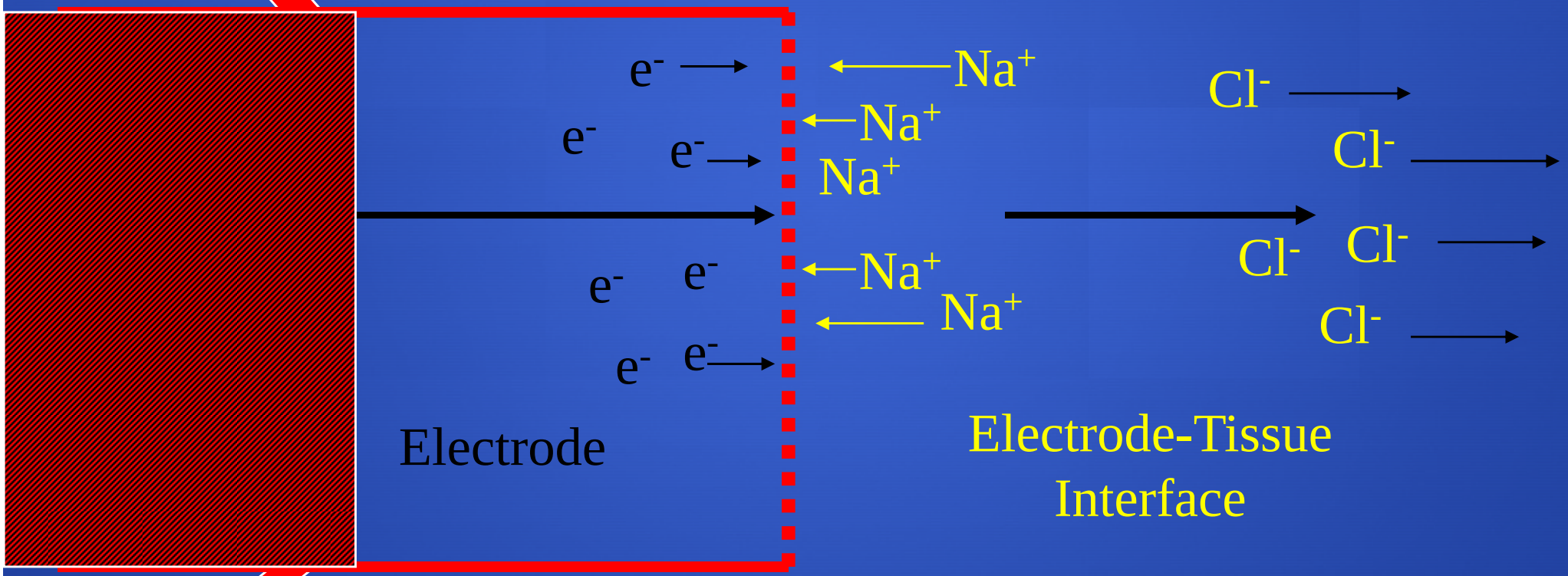
- Chronic threshold 2.5V & .2ms PW, PW programmed to .6ms providing a 2.1x safety margin.



Ohm's Law tattoo

Polarization

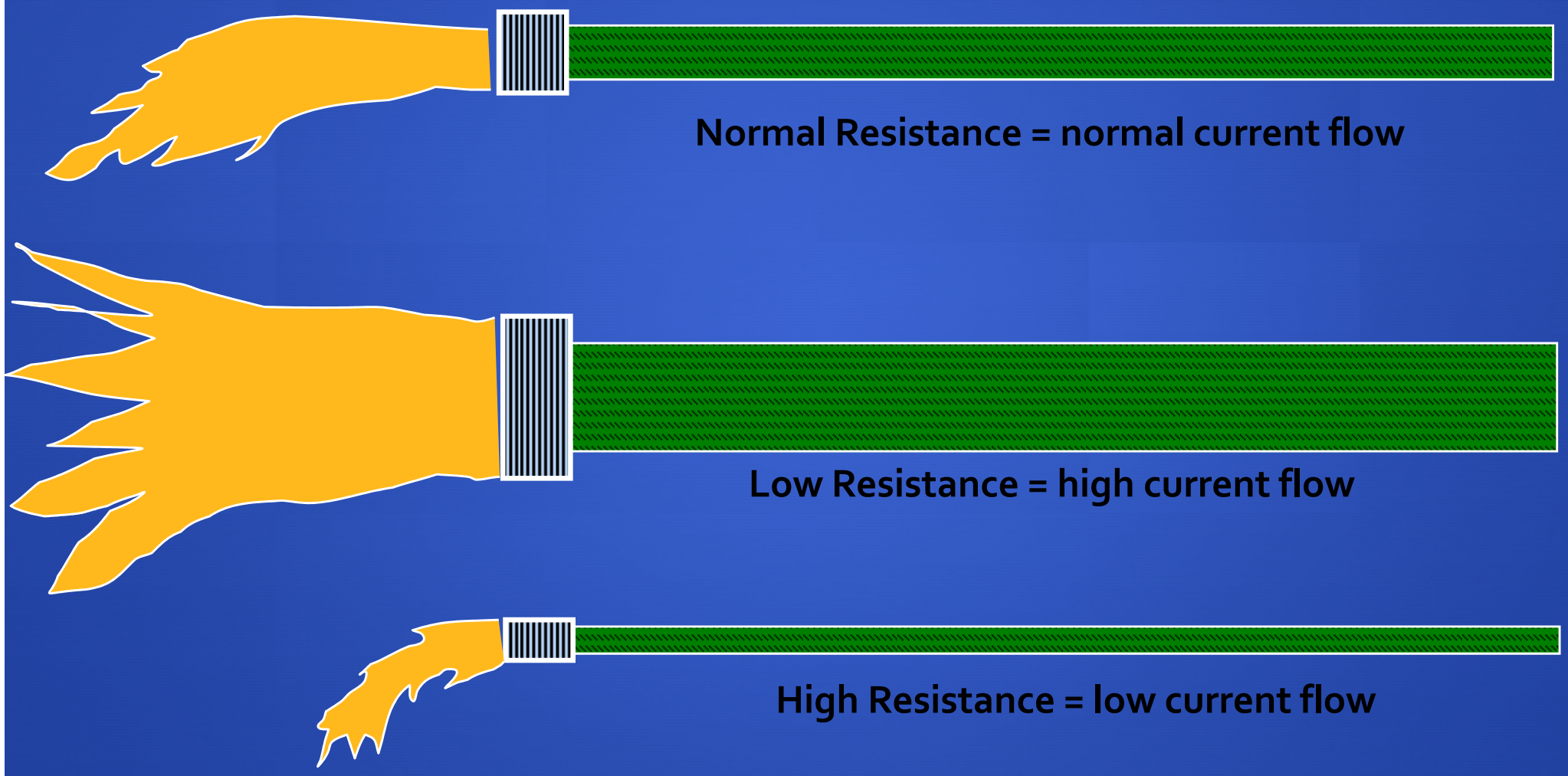
Capacitance effect: positively charged ions resist ion flow



Polarization/Afterpotential

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

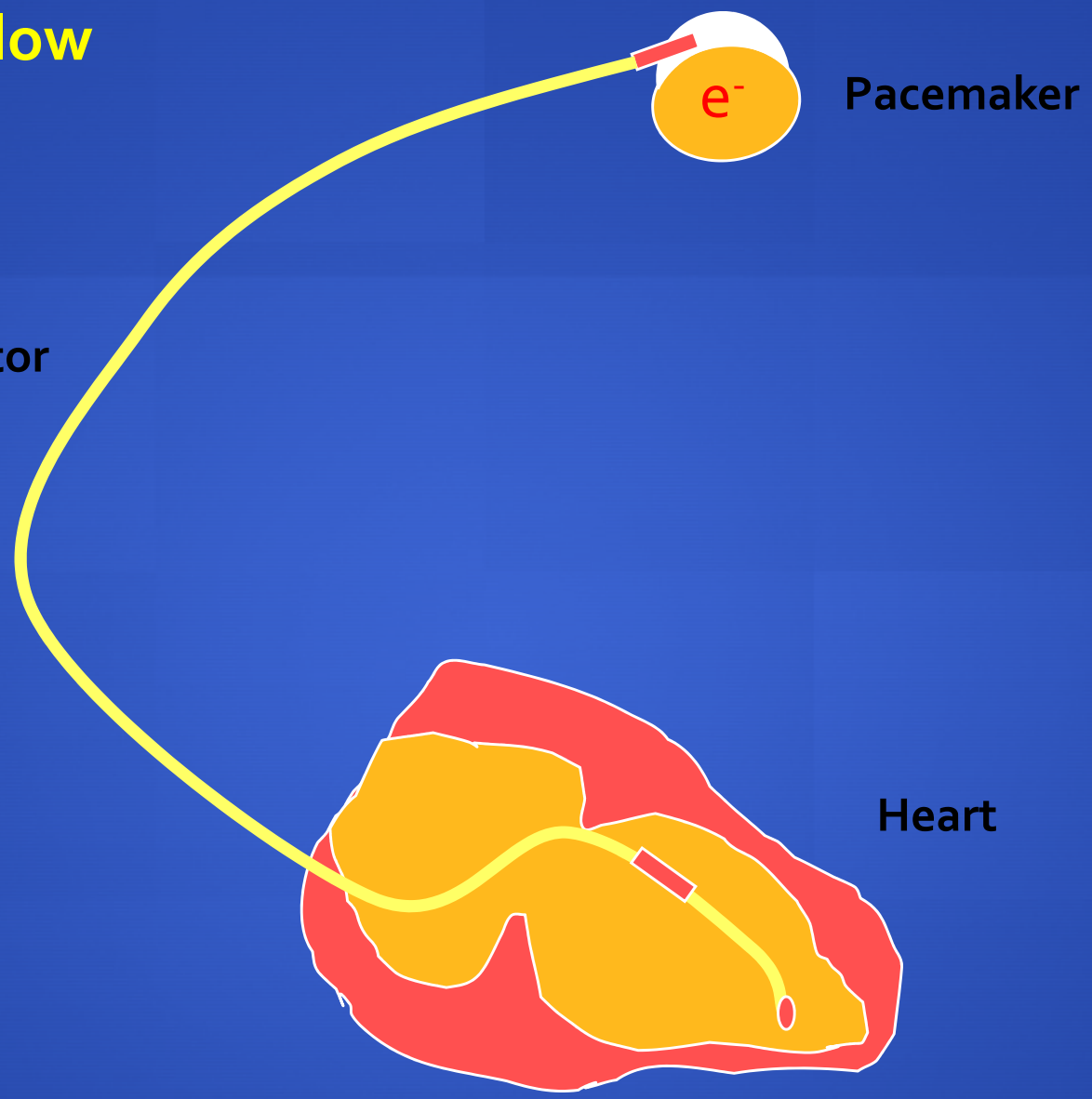
Garden Hose Analogy



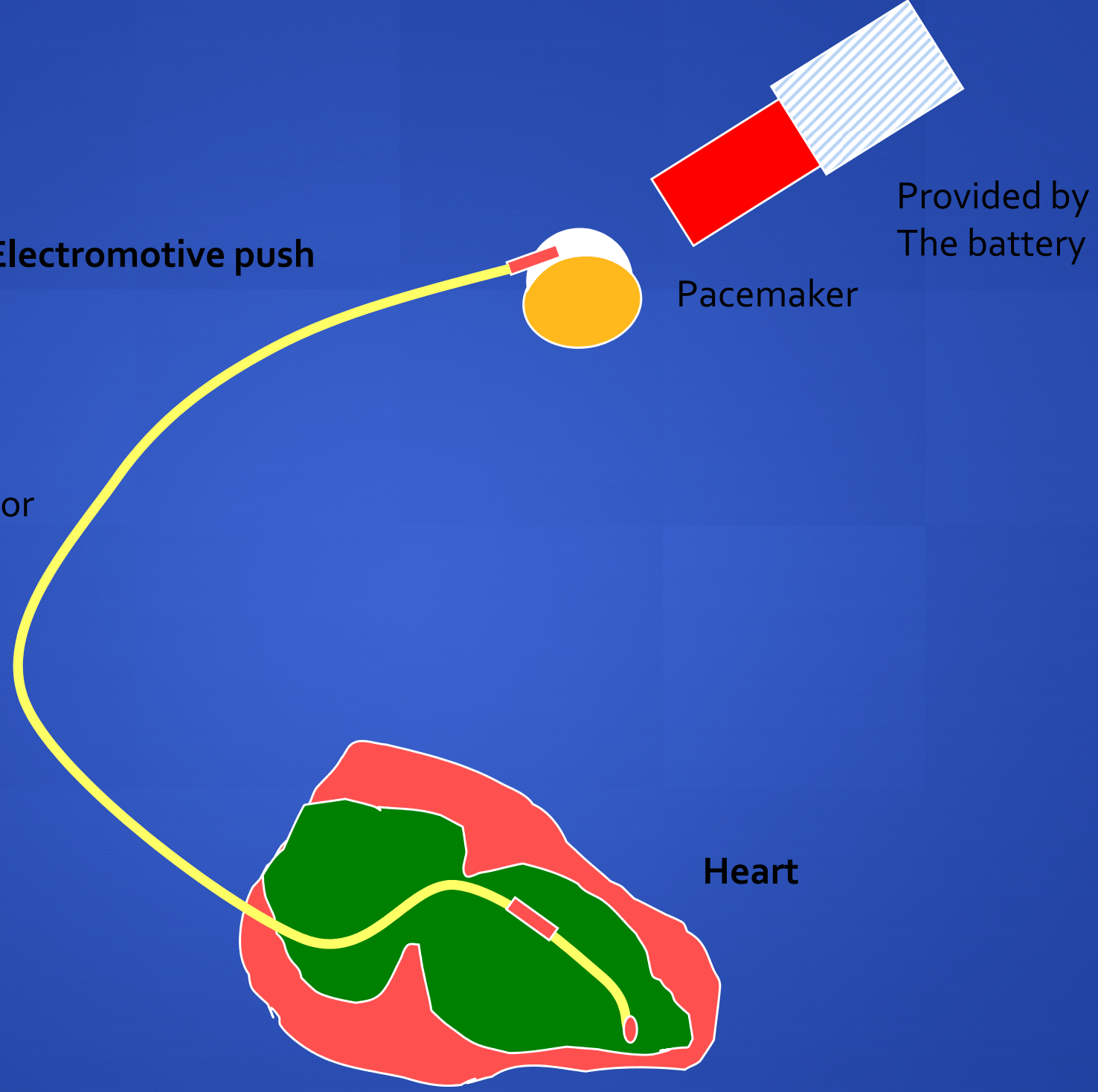
Fundamentals of Electronics

- <u>Terminology</u>
  - Current: flow of electrons through a circuit mA

Current Flow



Voltage: **Electromotive push**



$V = IR$ Ohm's Law

$V = 5.0\ mA \times .500\ Kohms$

$V = 2.5\ Volts$

Ohm's Law

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

$$R = \frac{V}{I} = \frac{2.5\,V}{10mA} = \frac{2.5\,V}{.01\,A} = 250\,\Omega$$

$$10\,mA \times \frac{1\,A}{1000\,mA}$$

$$.01\,A$$

Fundamentals of Electronics

- Energy: Voltage x Current x Time

$$E = V \times I \times t$$

Current in mA

Time in ms

Unit = Joule (J)

ENERGY & LONGEVITY

$$E = V \times I \times T \quad \text{or} \quad E = V^2 / R \times T$$

Case A: 2.5 V, 750 Ω, 0.5 ms

$$E = 6.25 / 750 \times 0.5$$

$$E = 4.2\ \mu J$$

Case B: 5.0 V, 750 Ω, 0.5 ms

$$E = 25 / 750 \times 0.5$$

$$E = 16.7\ \mu J$$

Four times the energy demand

46. Match the units: watt-second

a. energy

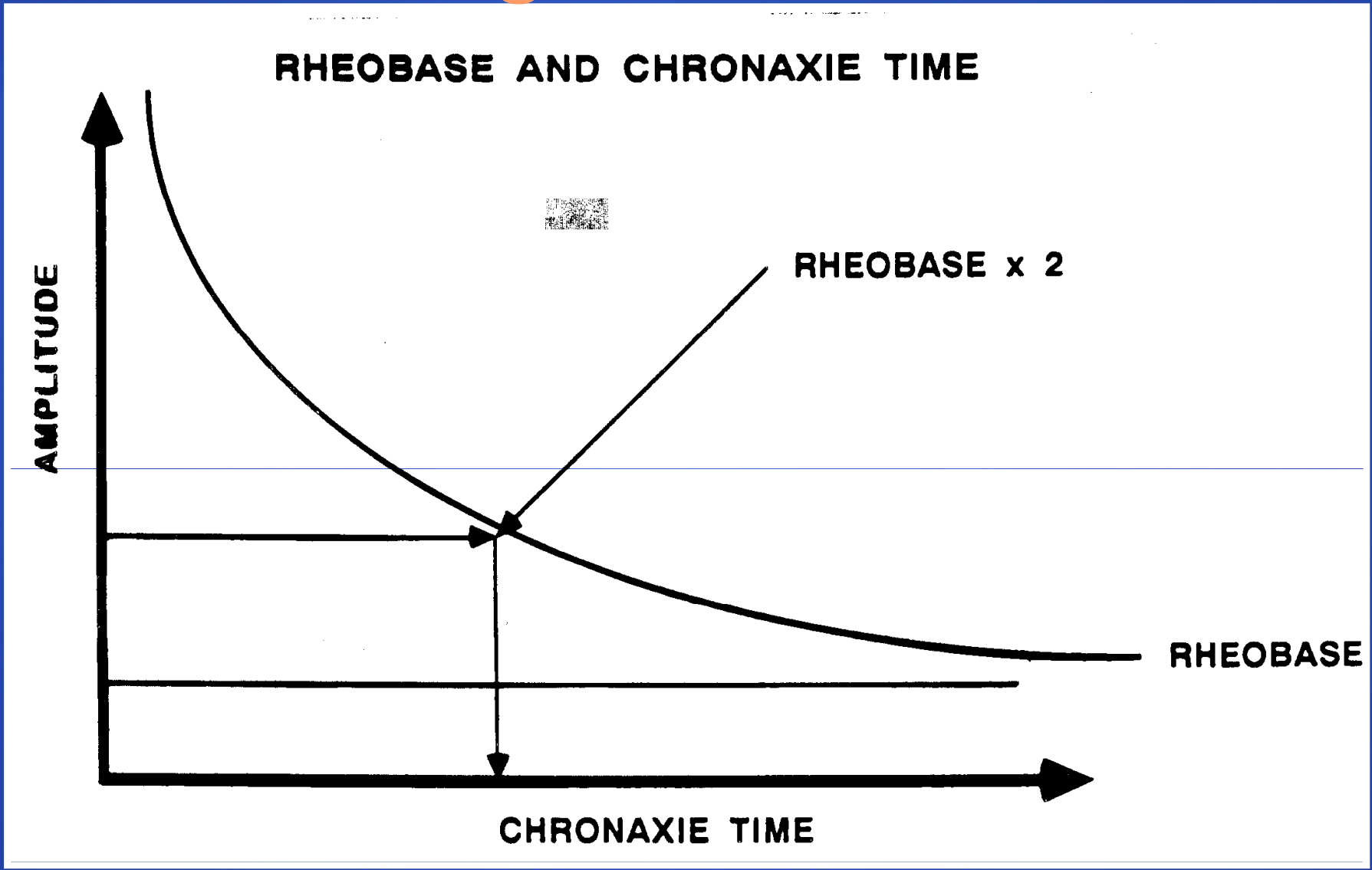
b. power

c. capacitance

d. current drain

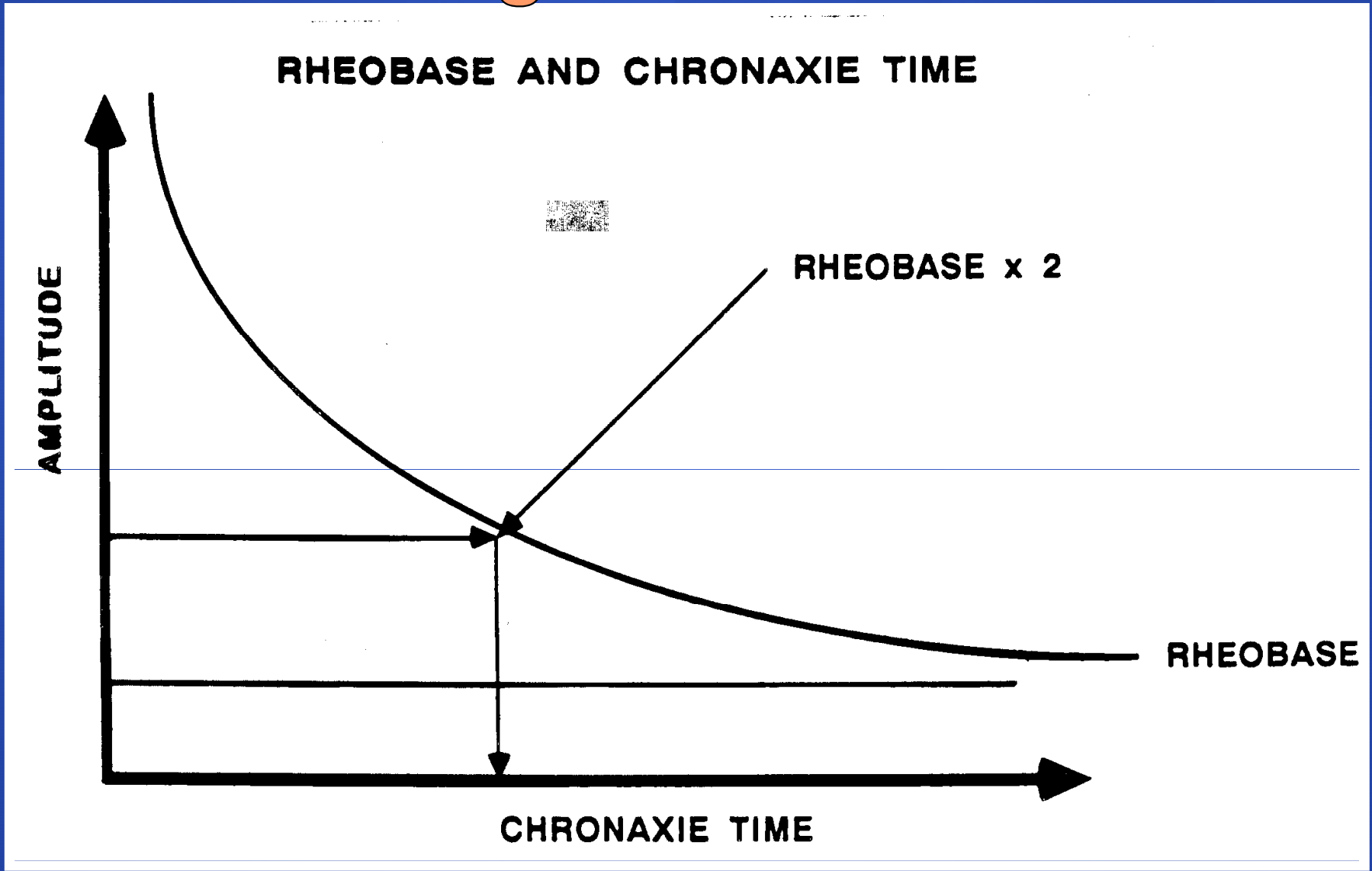
Q 45

Strength Duration

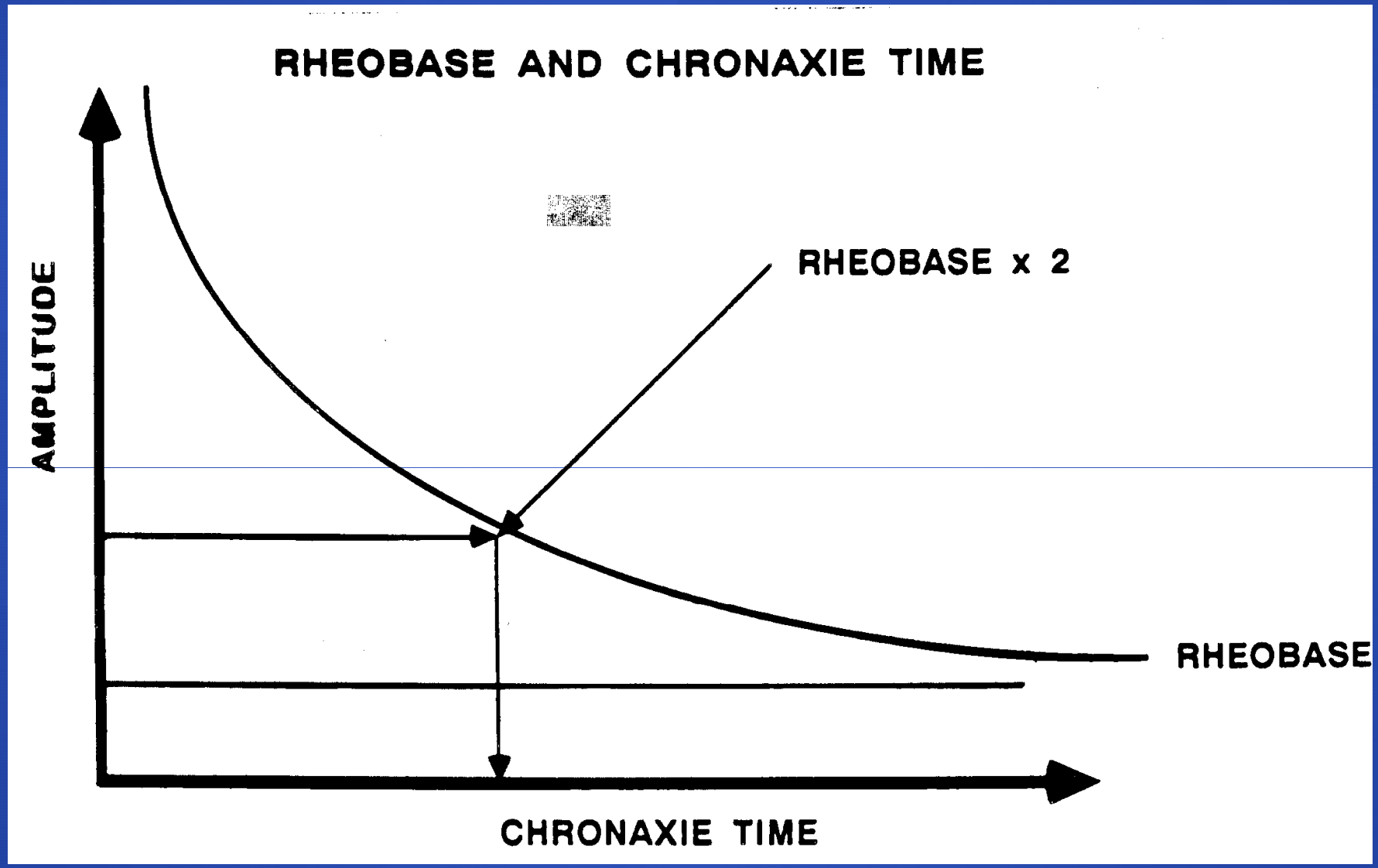


Q 62 & 63

Strength Duration



Strength Duration



- joule: unit of energy or work
- henry: unit of inductance (induced by a magnetic field)
- coulomb: unit of charge

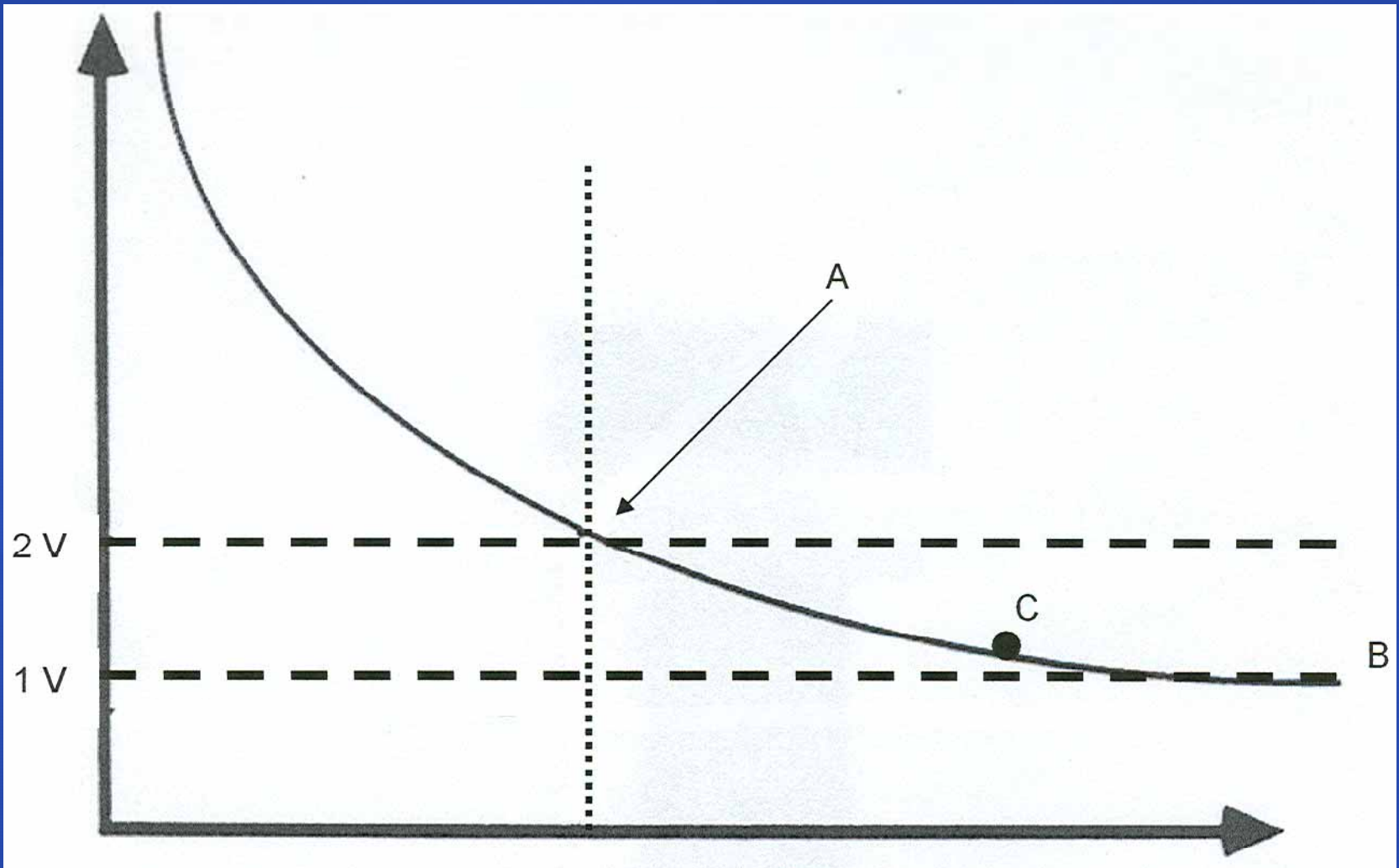
34. The rate at which work is done is is:

a. joule — unit of energy or work

b. farad — basic unit of capacitance

c. power

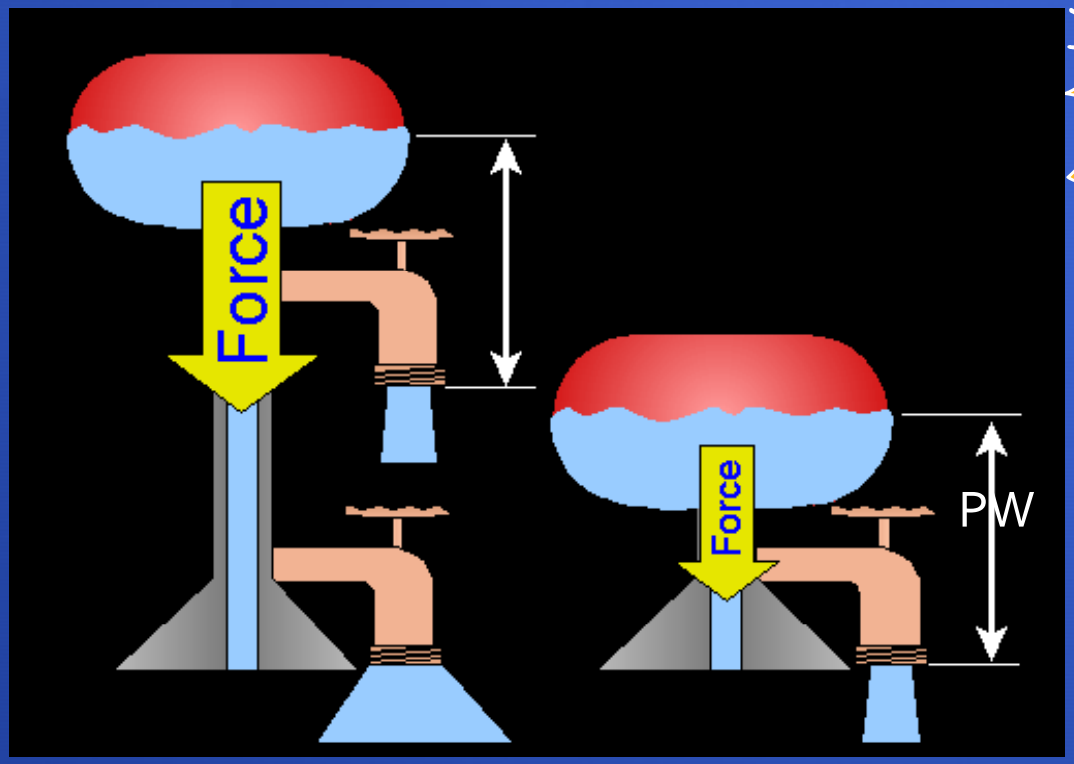
d. coulomb — unit of charge

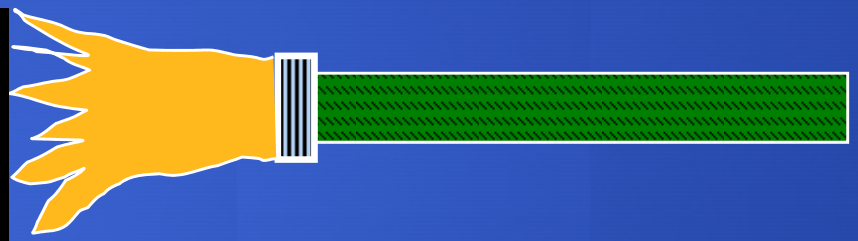


62. In the above figure line B represents the:

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[1]
- 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[1]
- Power: the rate of doing work or transmitting energy, a product of voltage & current usually expressed in watts[2]
- Watt: international unit of electrical power, watts are equivalent to joules per second[2]
- 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[2]
- Current drain: the average amount of current drawn from a battery by the external load; typically pacemakers draw from 10 – 30 microamperes[2]

1. In Ellenbogen K, et al. Clinical Cardiac Pacing, Defibrillation & CRT. 2007; pp 236
2. In Hayes &Asirvatham. Dictionary of Cardiac Pacing, Resynchronization, & Arrhythmias. 2007

Current I = V/R

Pacemaker 4.0 V = (I) 500 ohms
4.0 V/.500 Kohms = 8.0 mA

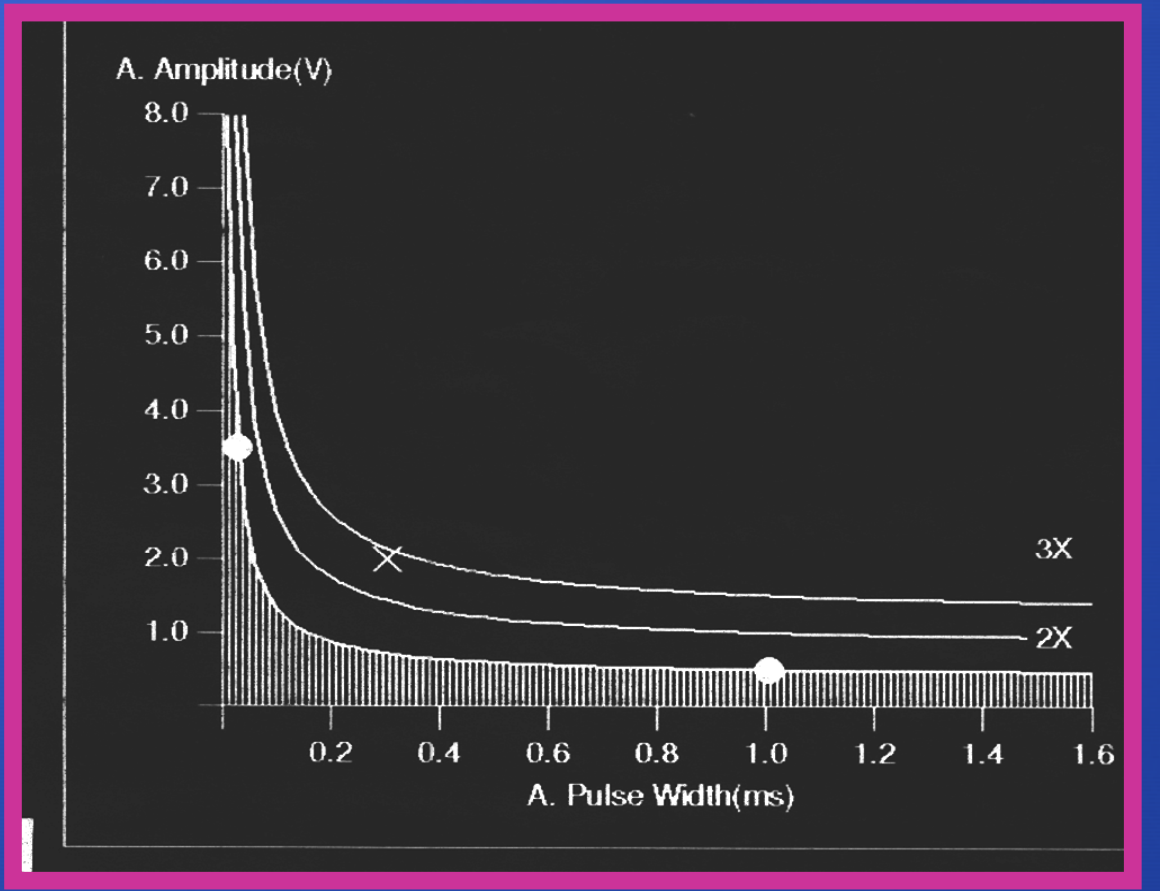
ICD 600-830 V i,e. 750 V = (I) 50 ohms
750 V/.050 Kohms = 15,000 mA

Pacemaker Longevity Factors

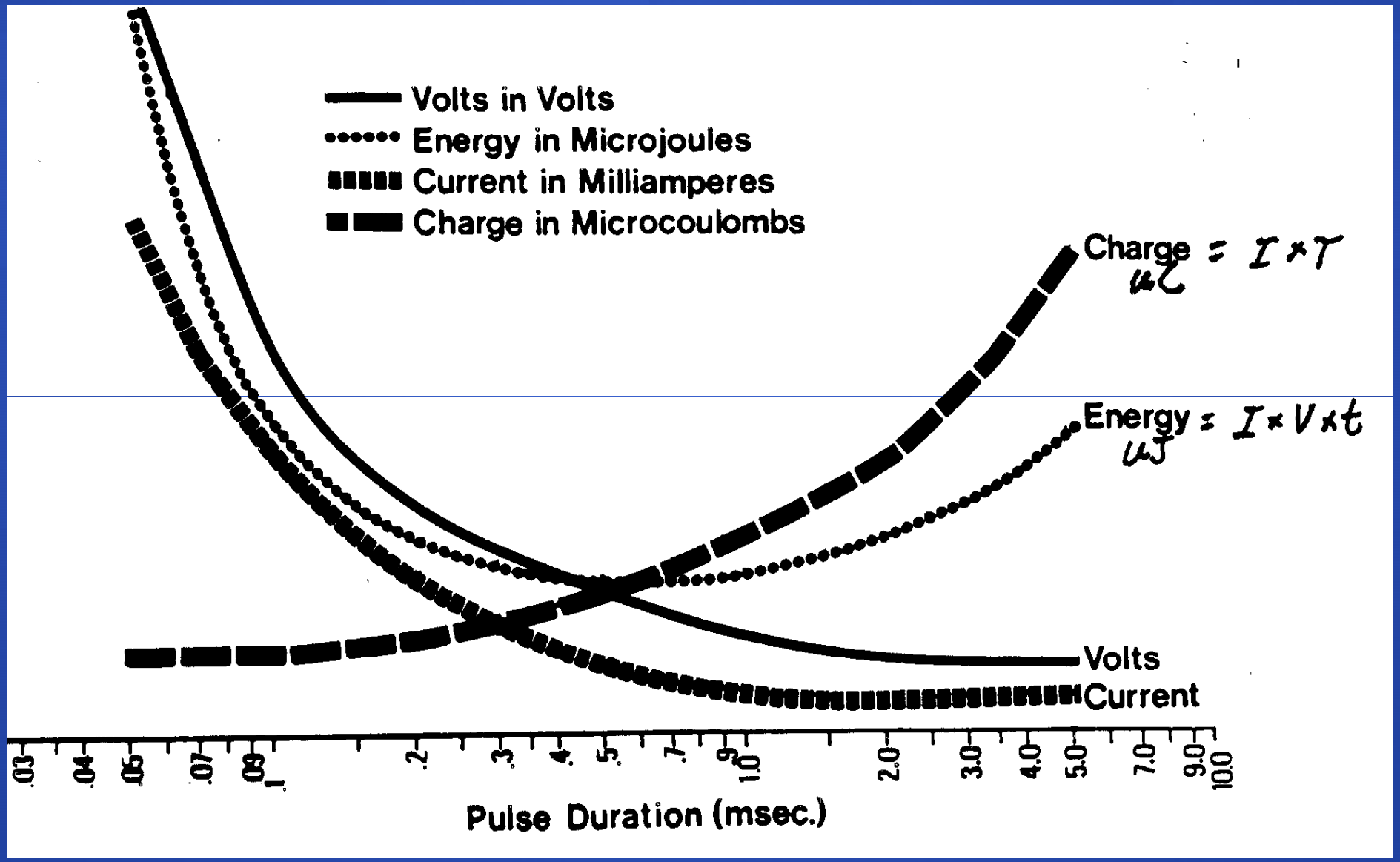
- Battery Capacity
- Rate of Drain
- Circuit Efficiency
- Pacing Rate
- Programmed output & Pulse Duration
- % of time pacing

45. The horizontal asymptote of a strength duration curve defines which of the following:

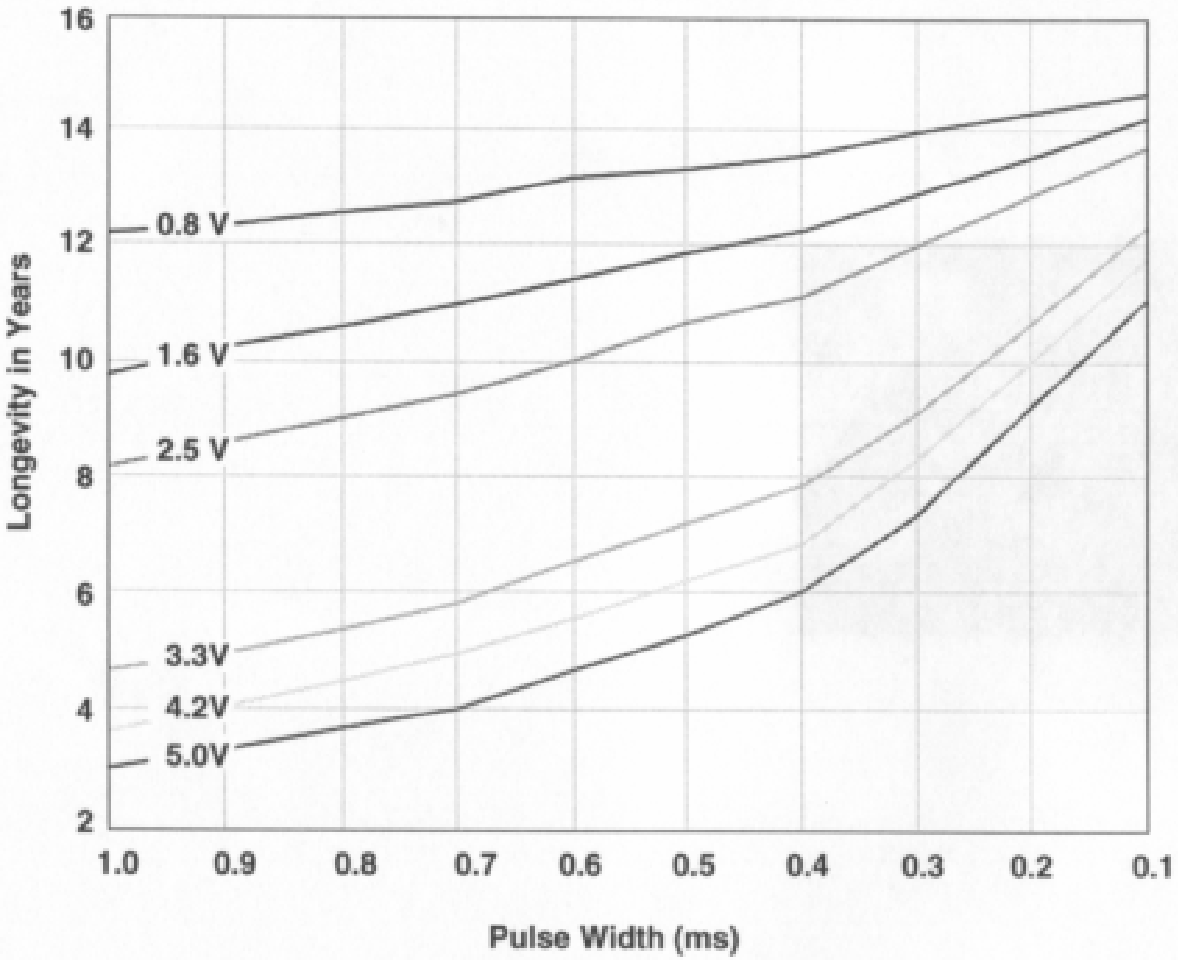
a. charge
b. pulse width threshold
c. rheobase
d. chronaxie



Strength Duration Curves



ESTIMATED LONGEVITY



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