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The Physics of Implantable Devices

By Martin James – Medtronic UK

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Innovating for life.

PACEMAKER BATTERIES

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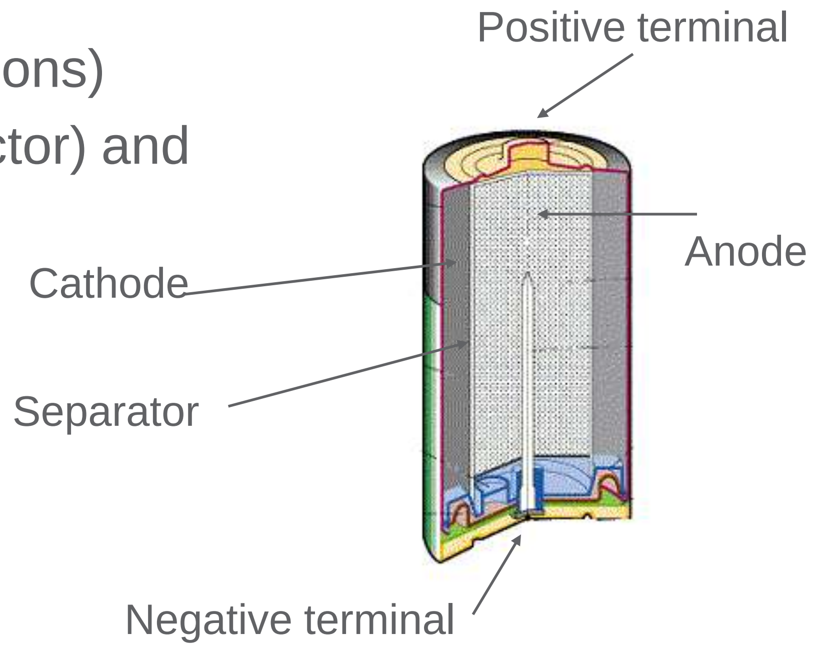
Pacemaker Batteries

- A battery produces electricity as a result of a chemical reaction. In its simplest form a battery consists of:
  - A negative electrode (anode)
  - An electrolyte, (which conducts ions)
  - A separator, (also an ion conductor) and
  - A positive electrode (cathode)



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Pacemaker Batteries

- Lithium Iodide chemistry
  - Long life
  - Predictable life
  - reliable

The ill-fated solar-powered pacemaker

ELECTRICAL CONCEPTS

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Voltage

- Voltage is the force or “push” that causes electrons to move through a circuit
- In a pacing system, voltage is:
  - Measured in volts
  - Represented by the letter “V”
  - Provided by the pacemaker battery
  - Often referred to as amplitude or pulse amplitude

Current

- The flow of electrons in a completed circuit
- In a pacing system, current is:
  - Measured in mA (milliamps)
  - Represented by the letter “I”
  - Determined by the amount of electrons that move through a circuit

Impedance

- The opposition to current flow
- In a pacing system, impedance is:
  - Measured in ohms
  - Represented by the letter “R” (Ω for numerical values)
  - The measurement of the sum of all resistance to the flow of current

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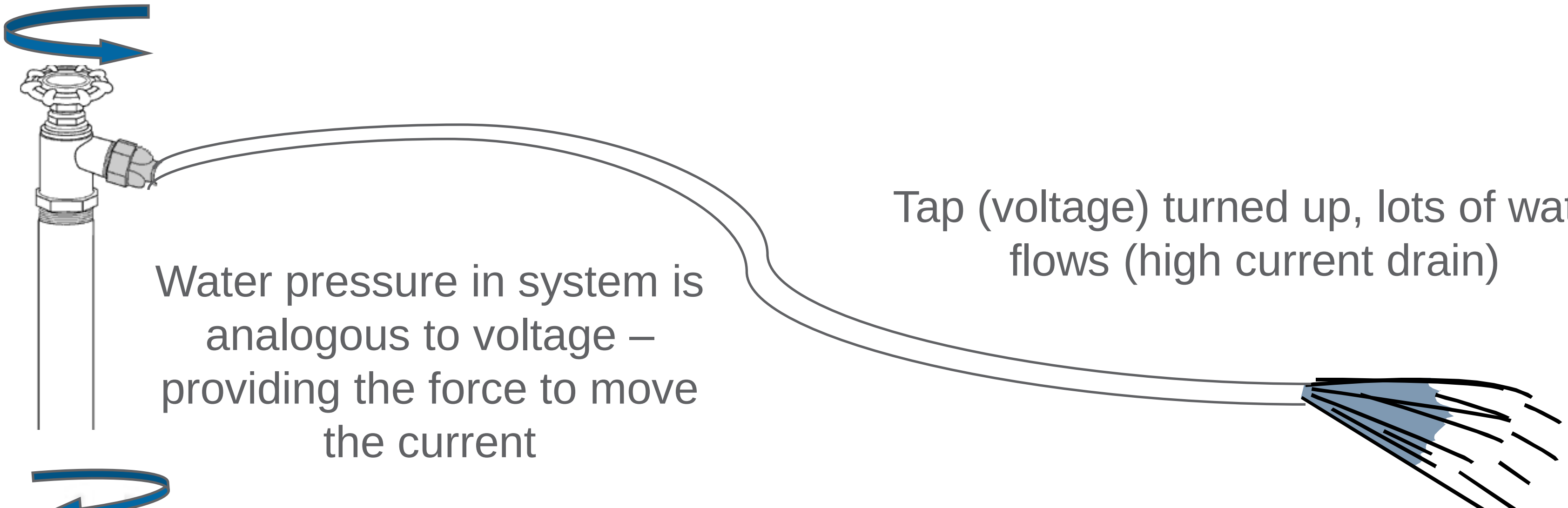
Voltage, Current, and Impedance are interdependent

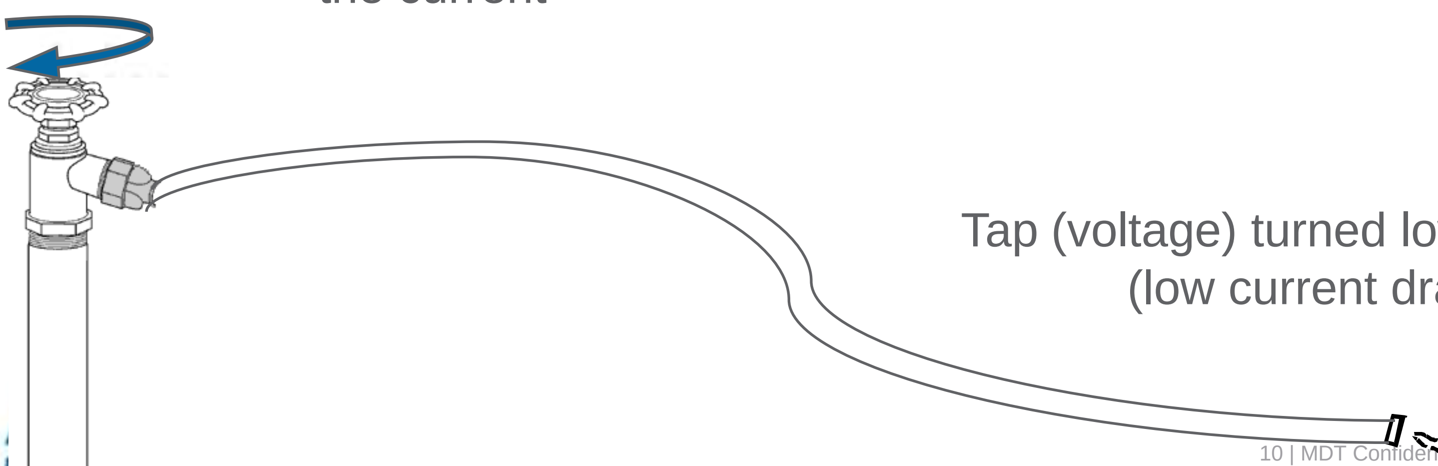
- The interrelationship of the three components is analogous to the flow of water through a hose
  - Voltage represents the force with which . . .
  - Current (water) is delivered through . . .
  - A hose, where each component represents the total impedance:
    - The nozzle, representing the electrode
    - The tubing, representing the lead wire

Voltage and Current Flow



Water pressure in system is analogous to voltage – providing the force to move the current

Tap (voltage) turned up, lots of water flows (high current drain)

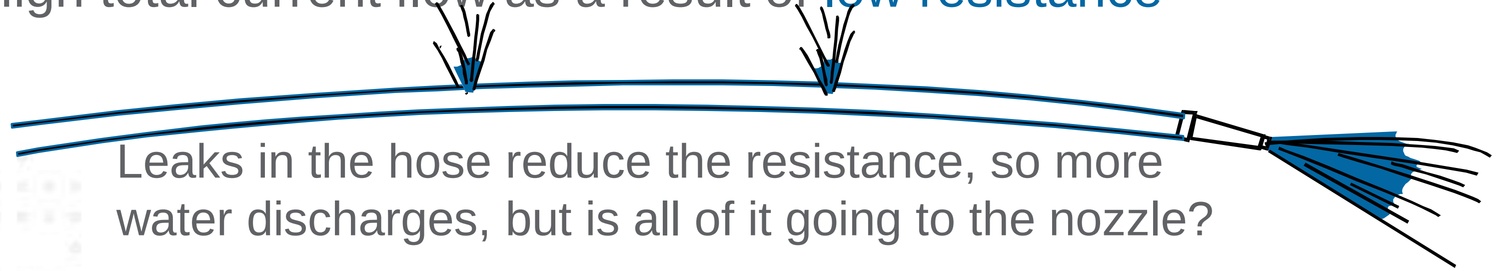


Tap (voltage) turned low, little flow (low current drain)

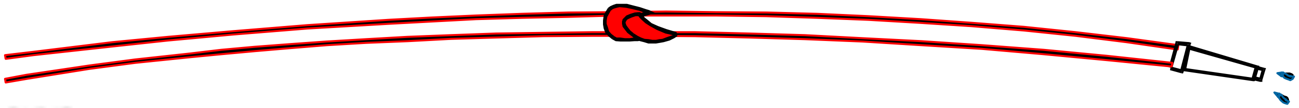
Resistance and Current Flow

Normal resistance – in this case the friction caused by the hose and nozzle

High total current flow as a result of low resistance



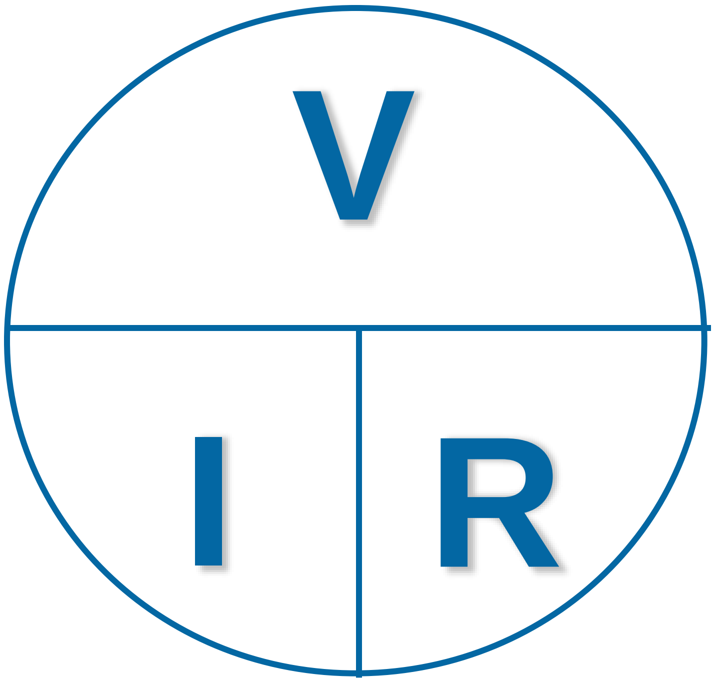
Leaks in the hose reduce the resistance, so more water discharges, but is all of it going to the nozzle?



High resistance, a knot, results in low total current flow

Ohm's Law

Describes the relationship between voltage and current and resistance



When Using Ohm's Law You Will Find That:

- If you reduce the voltage by half, the current is also cut in half
- If you reduce the impedance by half, the current doubles
- If the impedance increases, the current decreases

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Impedance Changes Affect Pacemaker Function and Battery Longevity

- High impedance reading reduces battery current drain and increases longevity
- Low impedance reading increases battery current drain and decreases longevity
- Impedance reading values range from 300 to 1,000 Ω
  - High impedance leads will show impedance reading values greater than 1,000 ohms

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Lead Impedance Values Will Change Due to:

- Insulation breaks
- Wire fractures

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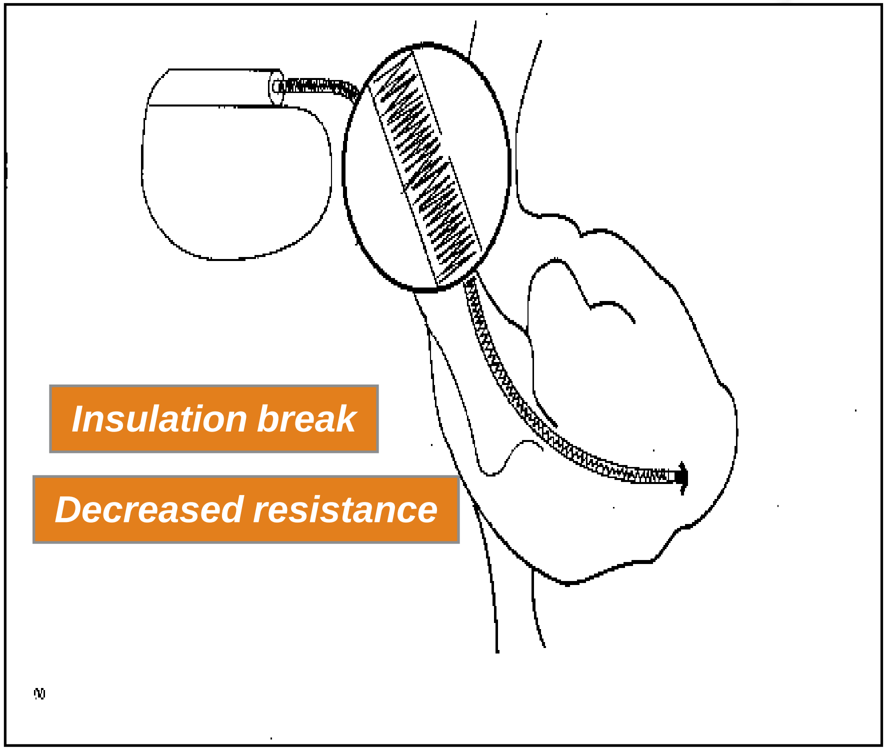
An Insulation Break Around the Lead Wire Can Cause Impedance Values to Fall

- Insulation breaks expose the wire to body fluids which have a low resistance and cause impedance values to fall
- Current drains through the insulation break into the body which depletes the battery
- An insulation break can cause impedance values to fall below 300 Ω



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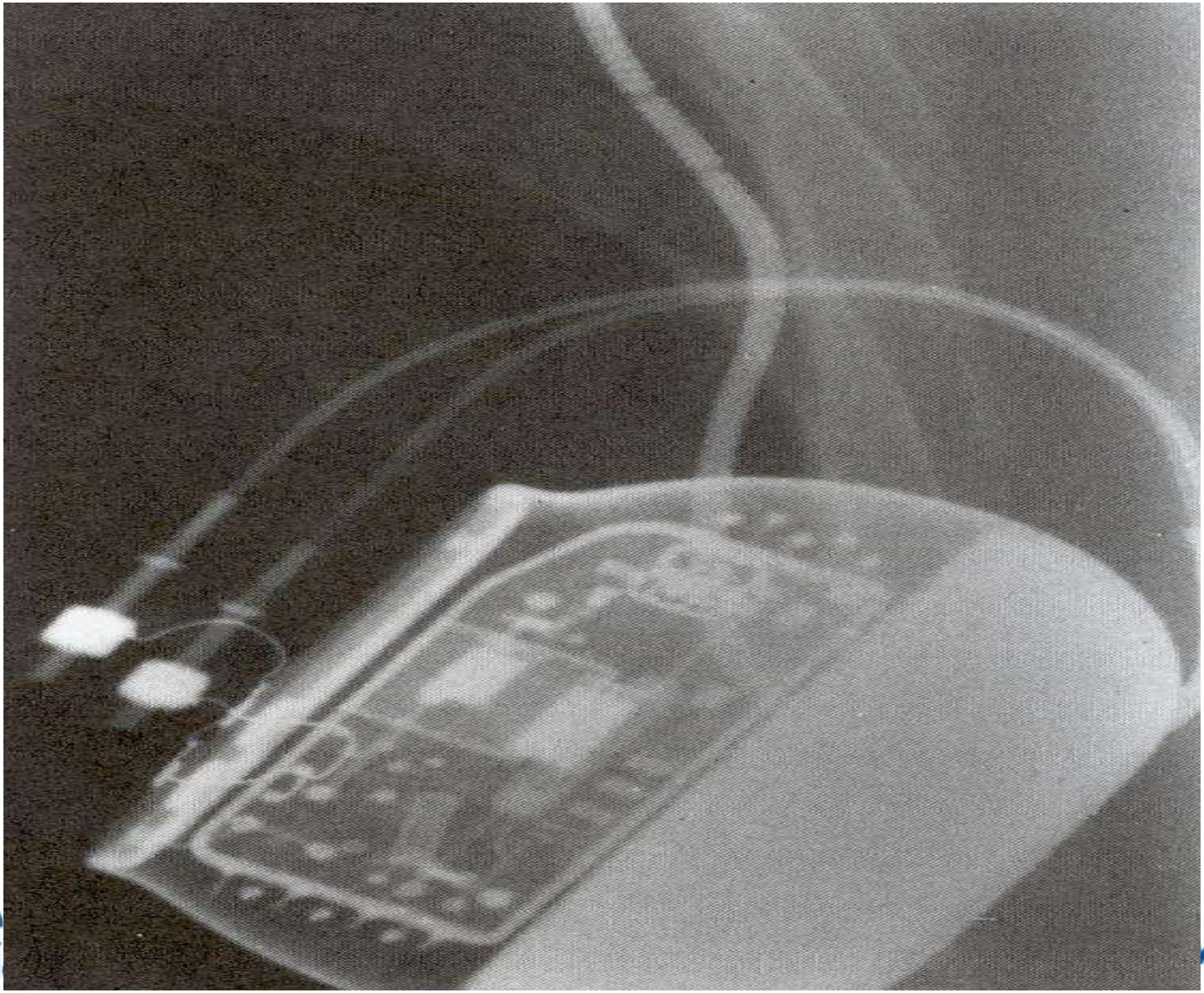
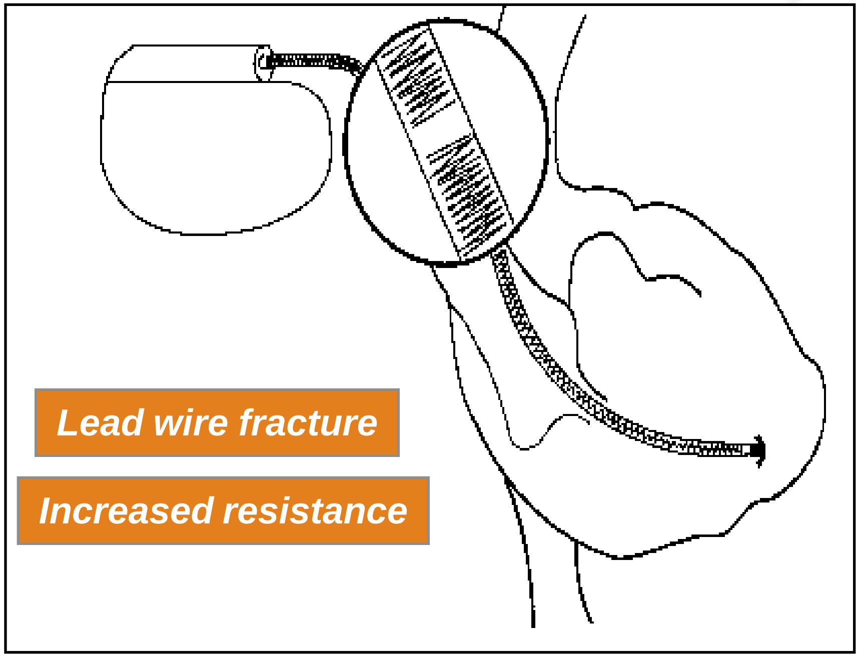
Insulation Break



A Wire Fracture Within the Insulating Sheath May Cause Impedance Values to Rise

- Impedance values across a break in the wire will increase
- Current flow may be too low to be effective
- Impedance values may exceed 3,000 Ω



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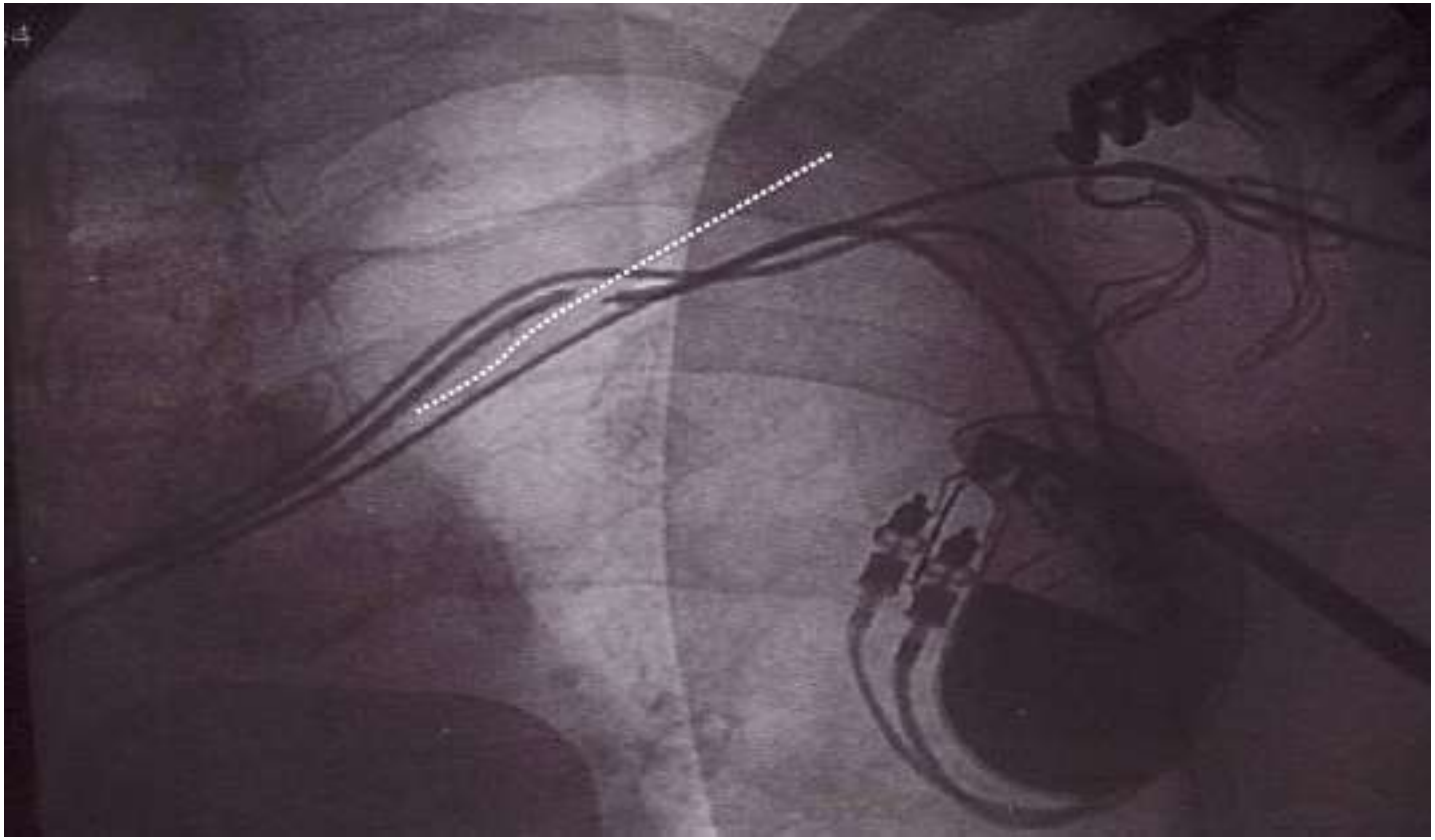
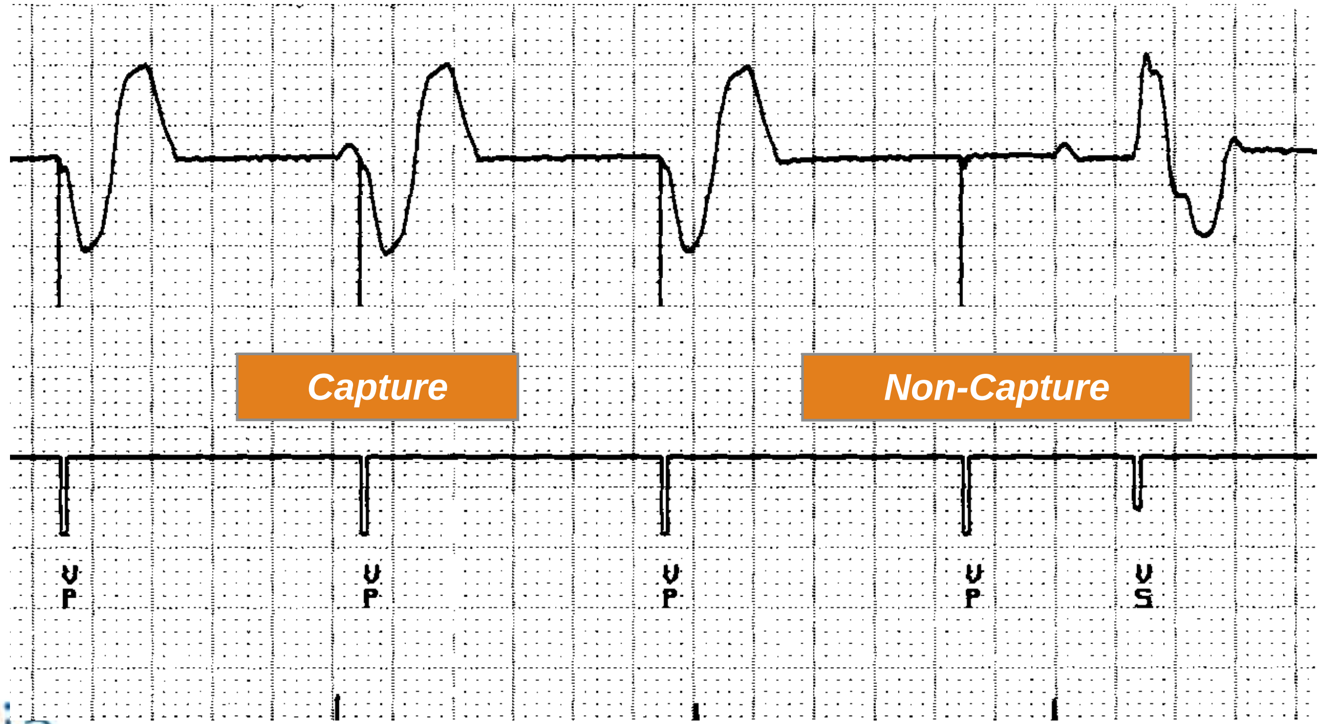
Lead Fracture



PACING

Stimulation Threshold

- The minimum electrical stimulus needed to consistantly capture the heart outside of the heart's refractory period

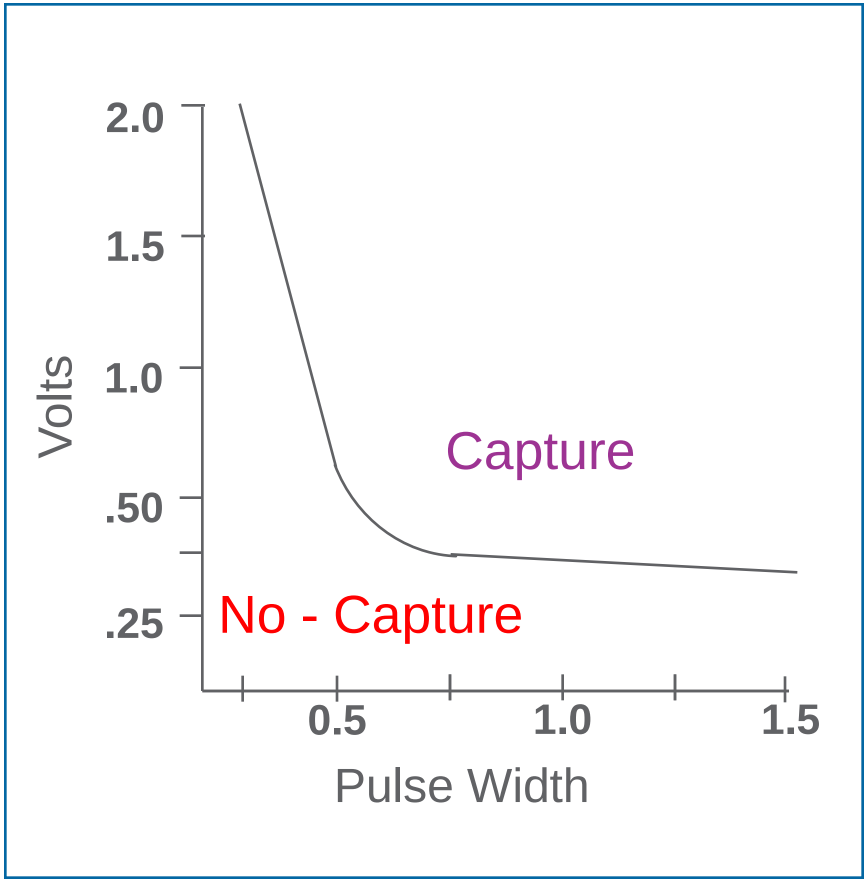


Myocardial Capture

- A function of:
  - Amplitude (Voltage) - the strength of the impulse:
    - The amplitude of the impulse must be large enough to cause depolarization (i.e., to “capture” the heart)
    - The amplitude of the impulse must be sufficient to provide an appropriate pacing safety margin
  - Pulse width - the duration of the current flow expressed in ms
    - The pulse width must be long enough for depolarization to disperse to the surrounding tissue

The Strength-Duration Curve

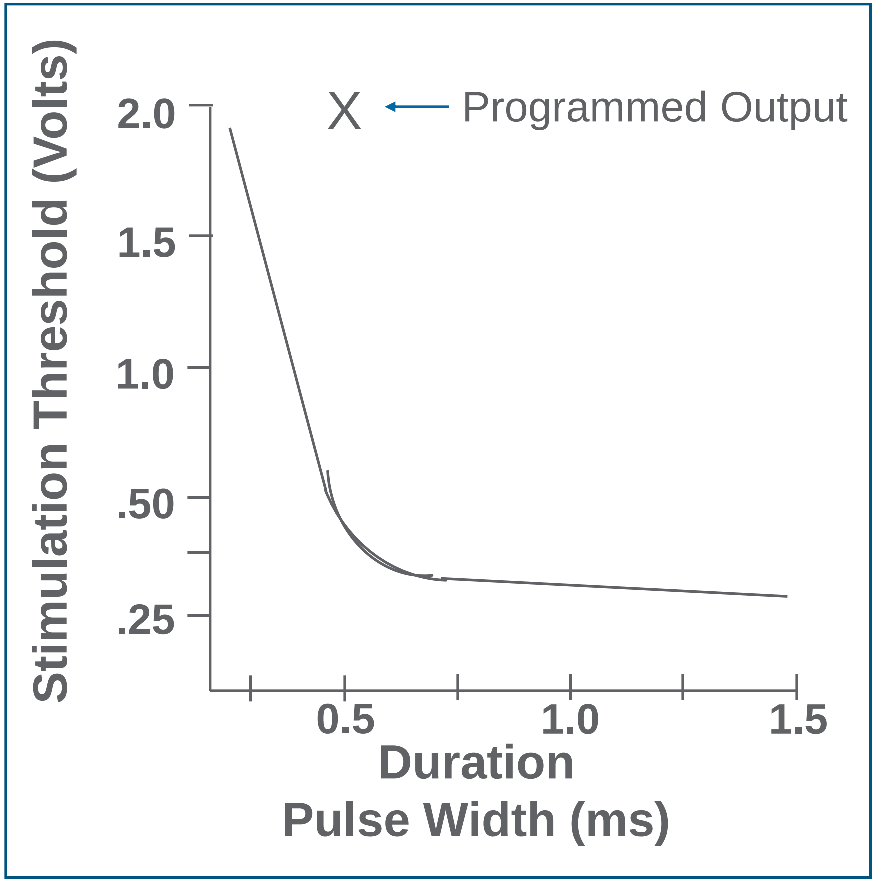
- The strength-duration curve illustrates the relationship of amplitude and pulse width
  - Any combination of pulse width and voltage on or above the curve will result in capture



Clinical Utility

of the Strength-Duration Curve

- By accurately determining capture threshold we can assure adequate safety margins because:
  - Thresholds differ in acute or chronic pacing systems
  - Thresholds fluctuate slightly daily
  - Thresholds can change due to metabolic conditions or medications



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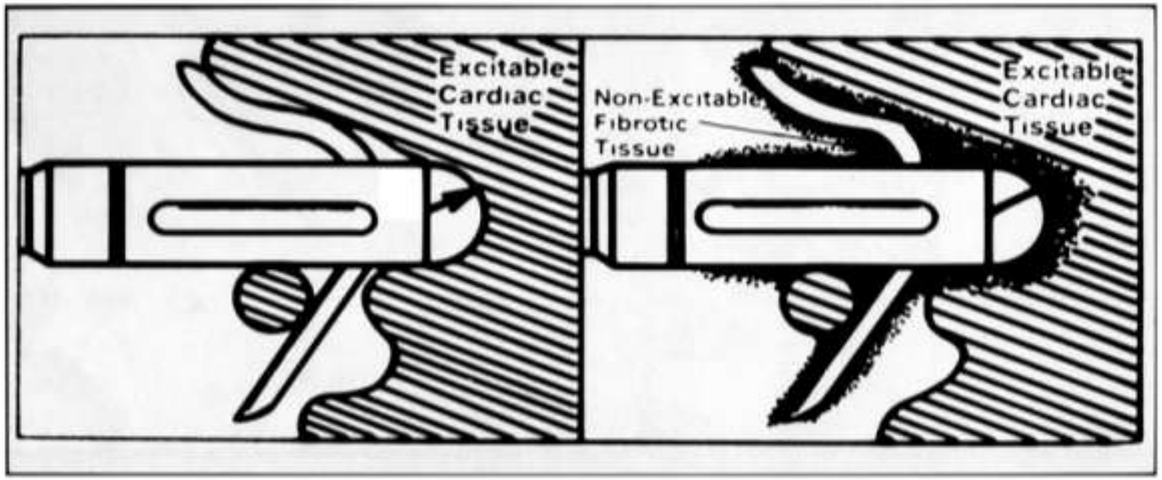
Effect of lead design on capture

- Lead maturation
  - Fibrotic “capsule” develops around the electrode following lead implantation
  - May gradually raise threshold
  - Usually no measurable effect on Impedance



Acute Chronic

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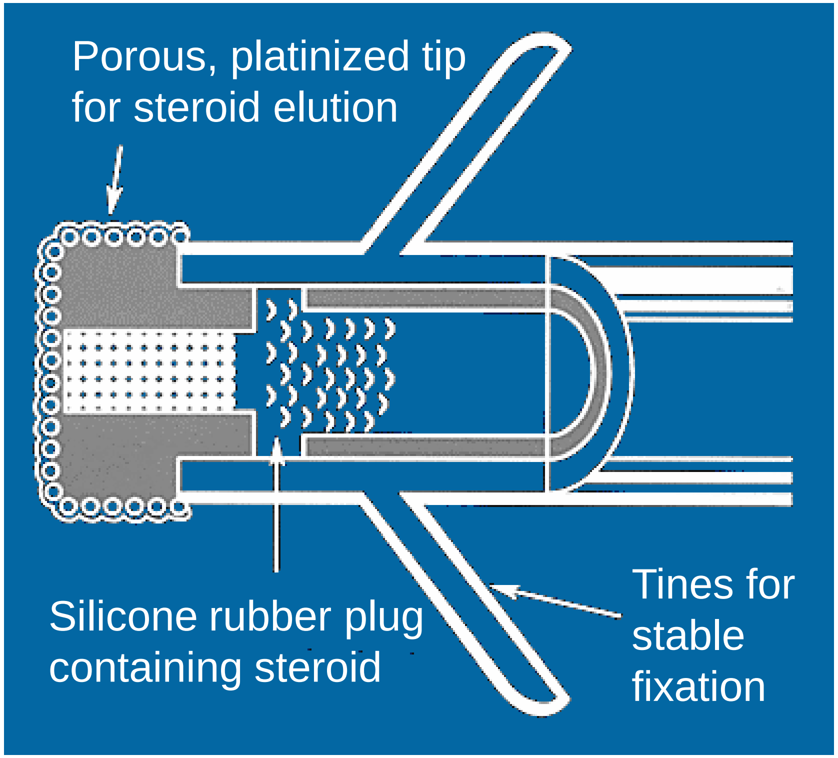
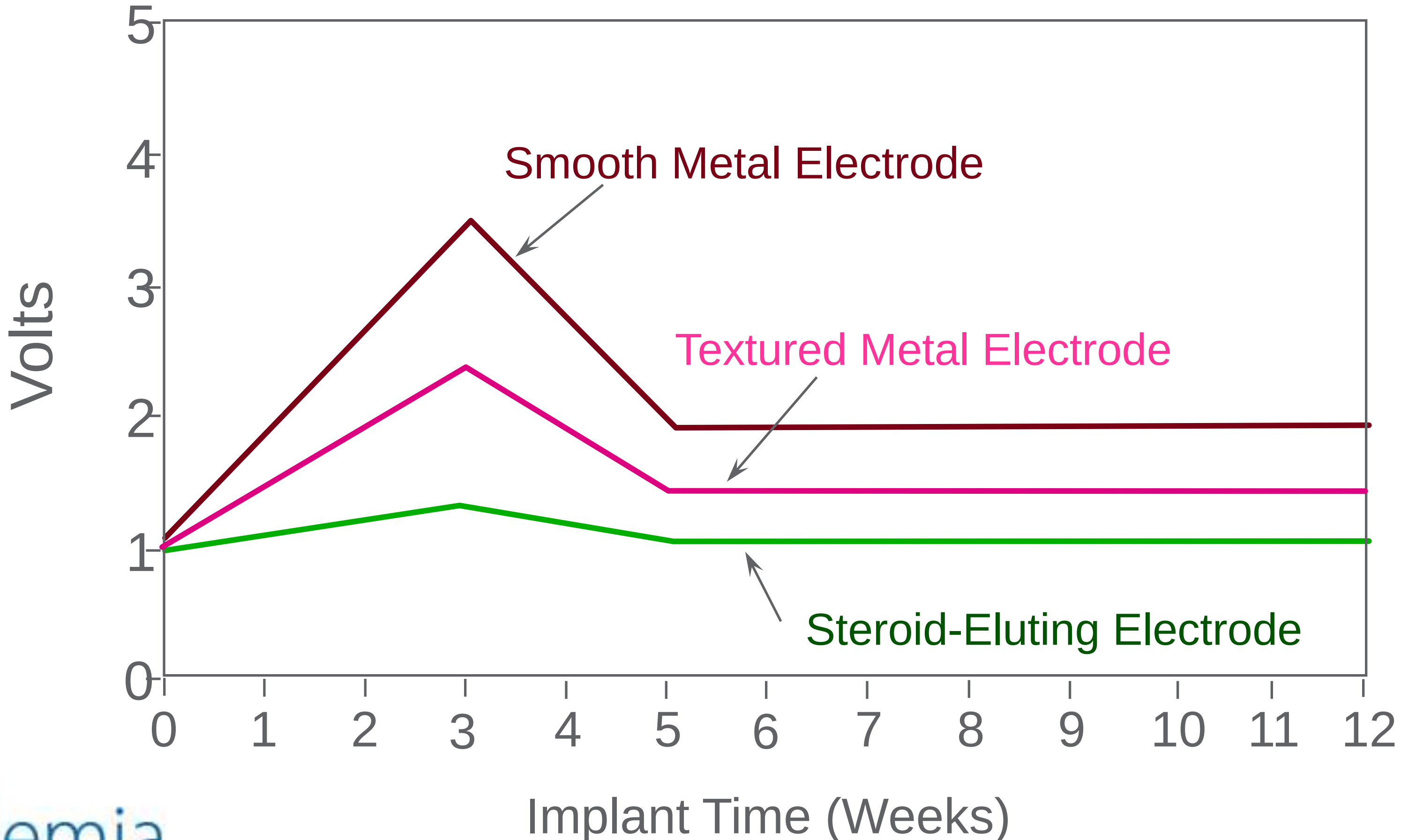
Steroid Eluting Leads

- Steroid eluting leads reduce the inflammatory process
  - Exhibit little to no acute stimulation threshold peaking
  - Leads maintain low chronic thresholds



Effect of Steroid on Stimulation Thresholds



Pulse Width = 0.5 msec

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Capture Hysteresis (The Wedensky Effect)

- The threshold measured when decreasing voltage is less than the threshold measured when increasing voltage (from a sub threshold voltage)

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SENSING

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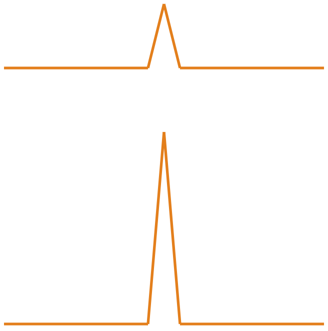
Pacemaker Sensing

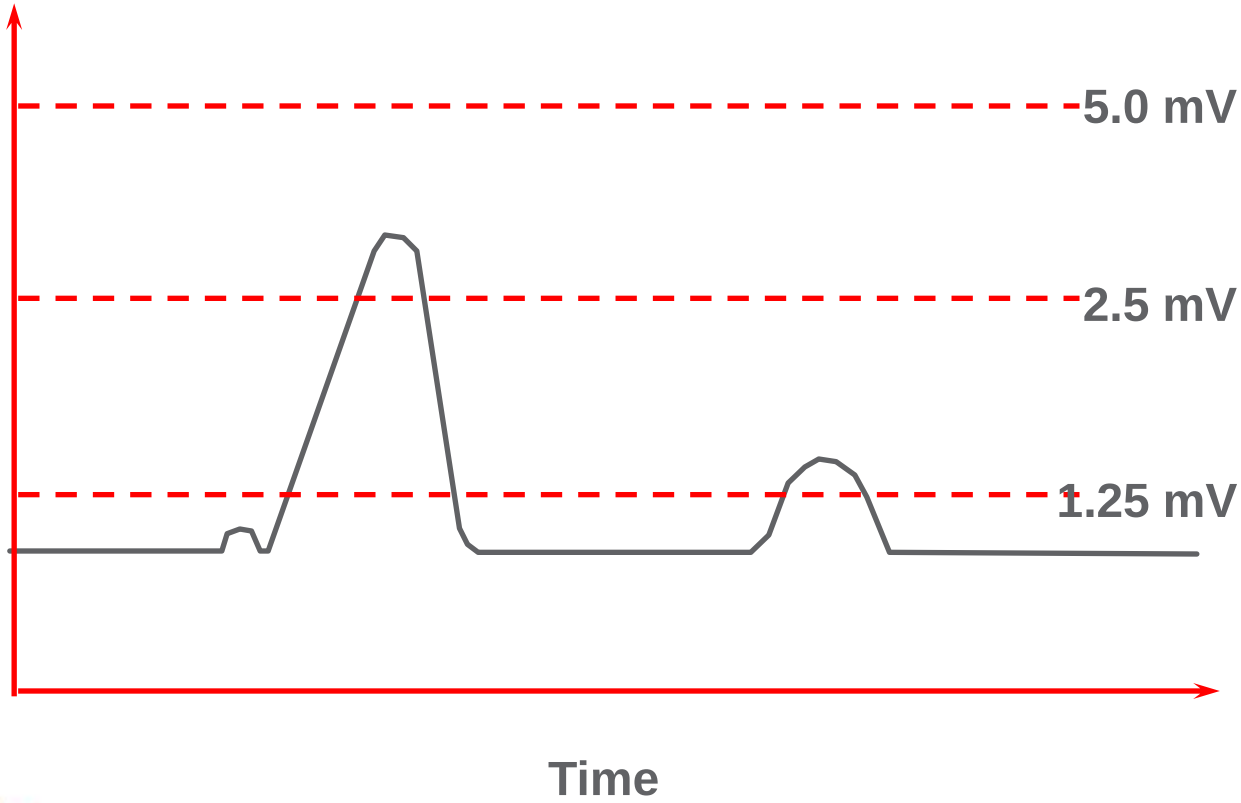
- Refers to the ability of the pacemaker to “see” signals
  - Expressed in millivolts (mV)
- The millivolts (mV) refers to the <u>size</u> of the signal the pacemaker is able to “see”

0.5 mV signal

2.0 mV signal



Sensitivity – the value we program into the IPG

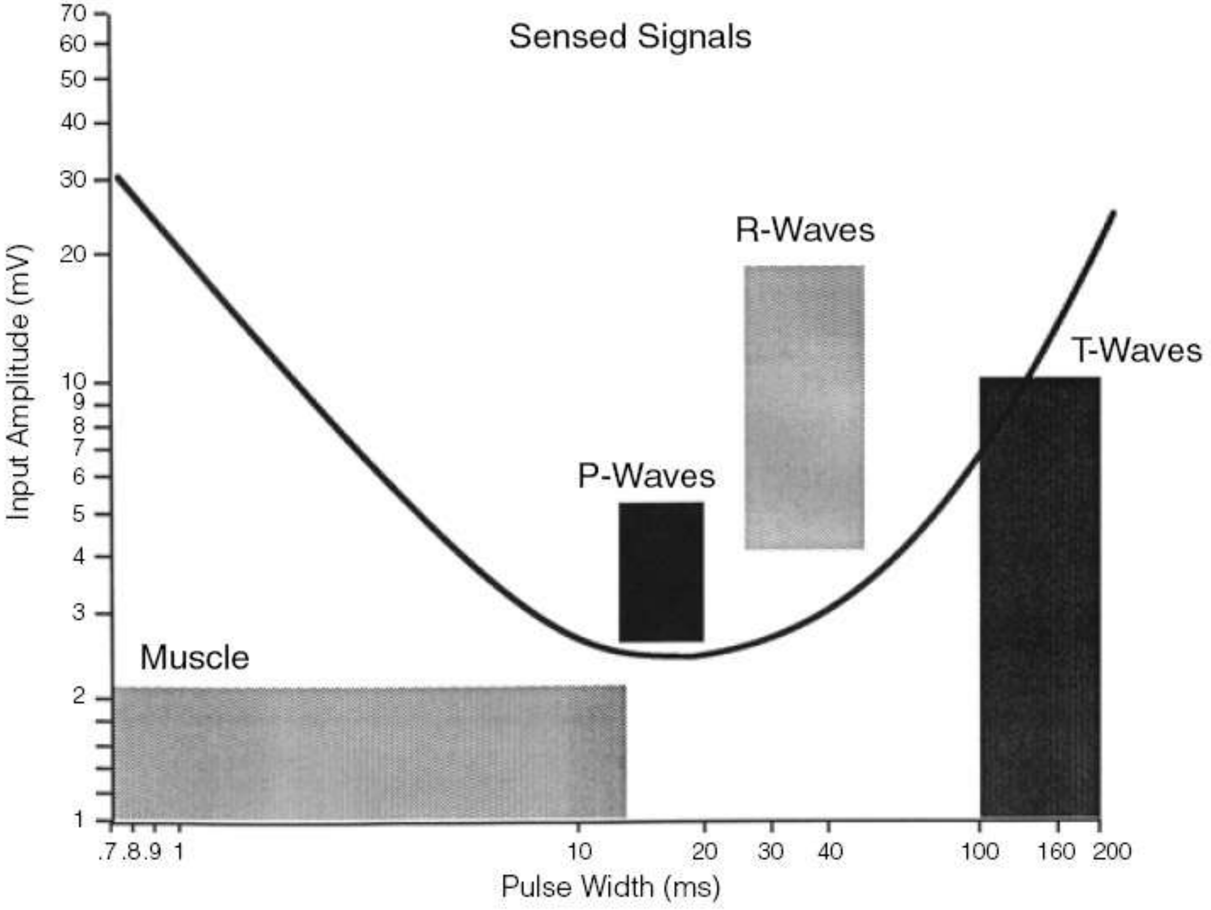


Sensing Amplifiers/Filters

- Accurate sensing requires that extraneous signals are filtered out
  - Because whatever a pacemaker senses is by definition a P- or an R-wave
  - Sensing amplifiers use filters that allow appropriate sensing of P waves and R waves and reject inappropriate signals

- Unwanted signals most commonly sensed are:
  - T waves (which the pacemaker defines as an R-wave)
  - Far-field events (R waves sensed by the atrial channel, which the Pacemaker thinks are P-waves)
  - Skeletal muscle myopotentials (e.g., from the pectoral muscle etc. which the pacemaker may think is either P- or R-waves)
  - Signals from the pacemaker – eg. a ventricular pacing spike sensed on the atrial channel “crosstalk”

Pacemaker sensing



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POLARIZATION

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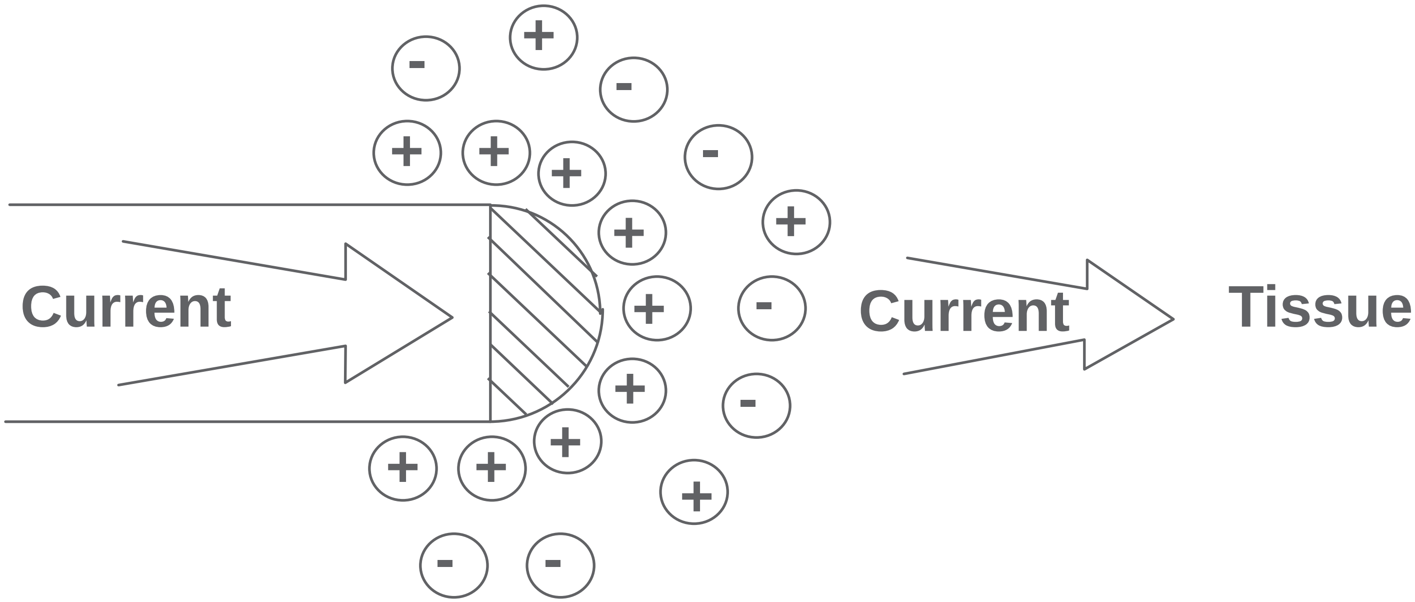
Polarization



Polarization Layering Effect

ICD PHYSICS

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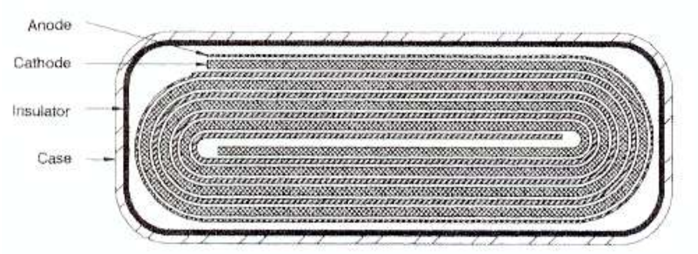
ICD Battery Design

- Lithium/Silver Vanadium Oxide
- Anode: Lithium
- Cathode: Silver Vanadium Oxide
- Electrically Insulated via Porous separator
- Porous Separator allows ions Flow.
- High Power to Achieve Short Charge time, High surface area



ICD Sensing

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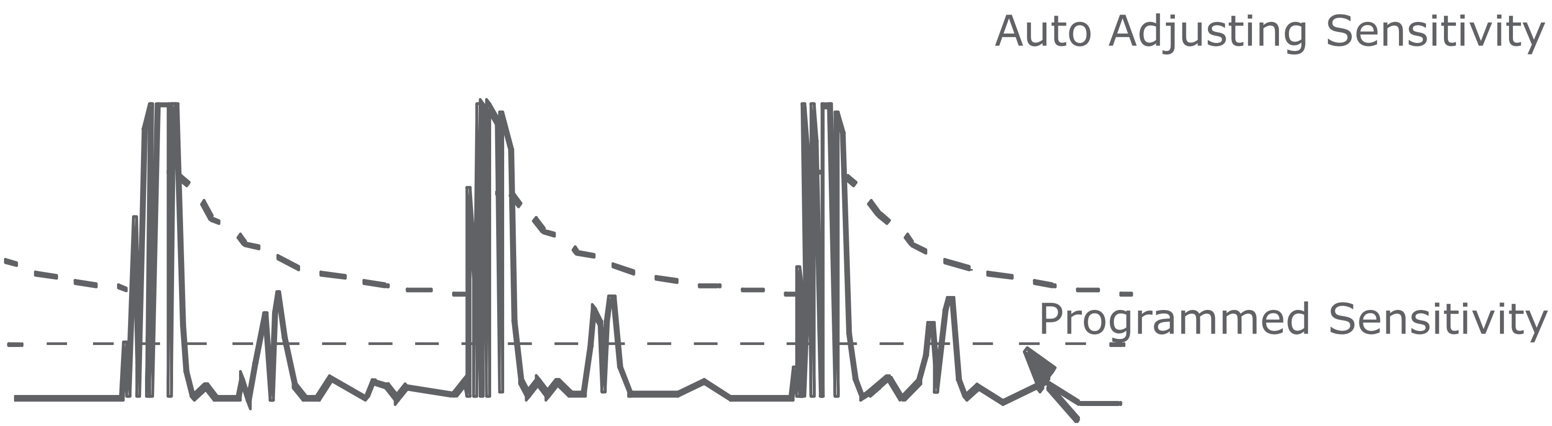
Auto-Adjusting Sensitivity

Ventricular

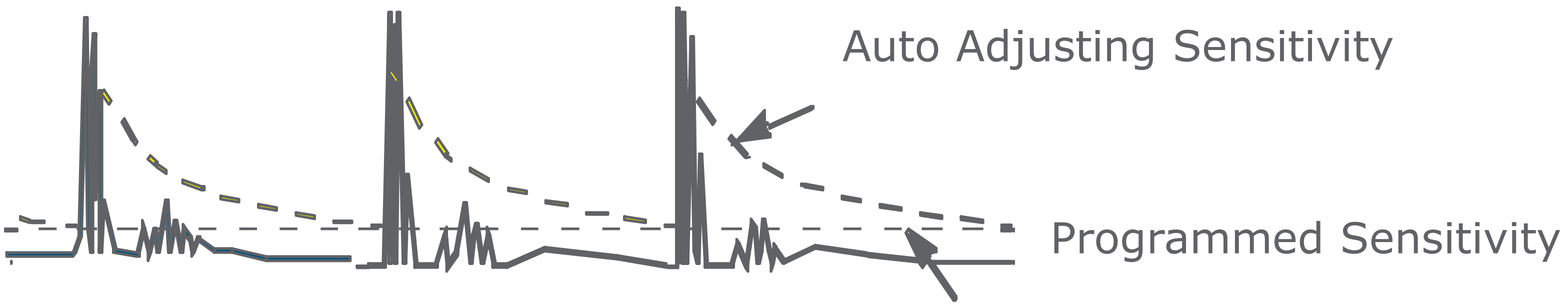
Filtered and Rectified Ventricular Electrogram



Auto-Adjusting Sensitivity

<u>Atrial</u>

Filtered and Rectified Atrial Electrogram —



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Defibrillation Threshold

The Minimum Electrical Dosage required to defibrillate the heart

General recommendation (safety margin)

The device should have a maximum output at least 10 Joules higher then the defibrillation threshold

$$35J \geq \mathit{DFT} + 10\ \mathit{Joules}$$

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Probability and defibrillation

- Pacing is an all or none phenomenon
  - At a particular pulse amplitude and duration you either capture myocardium every time or you don't
  - Concept of threshold
- Defibrillation is a probabilistic phenomenon
  - No energy is guaranteed to successfully defibrillate every time

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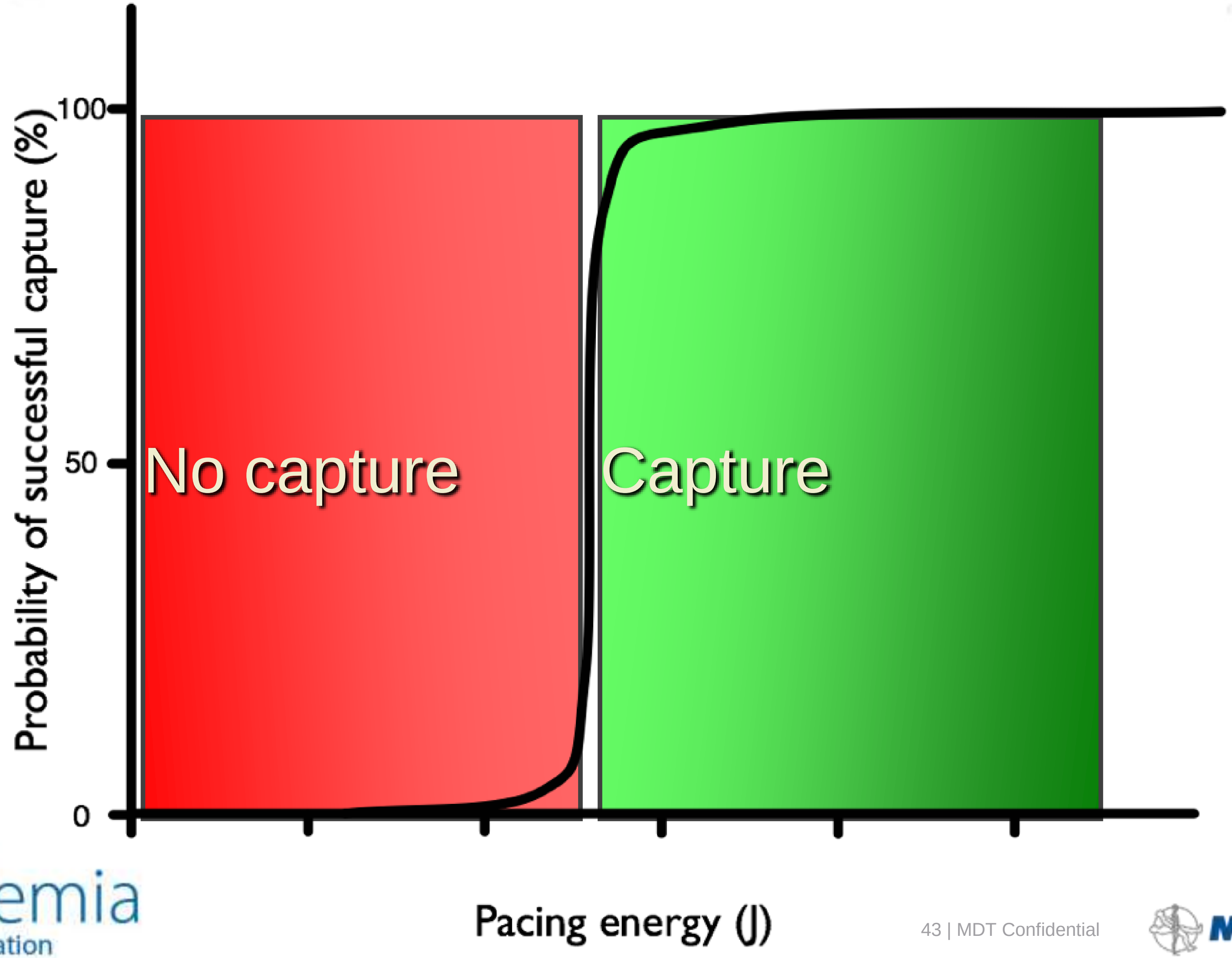
Pacing



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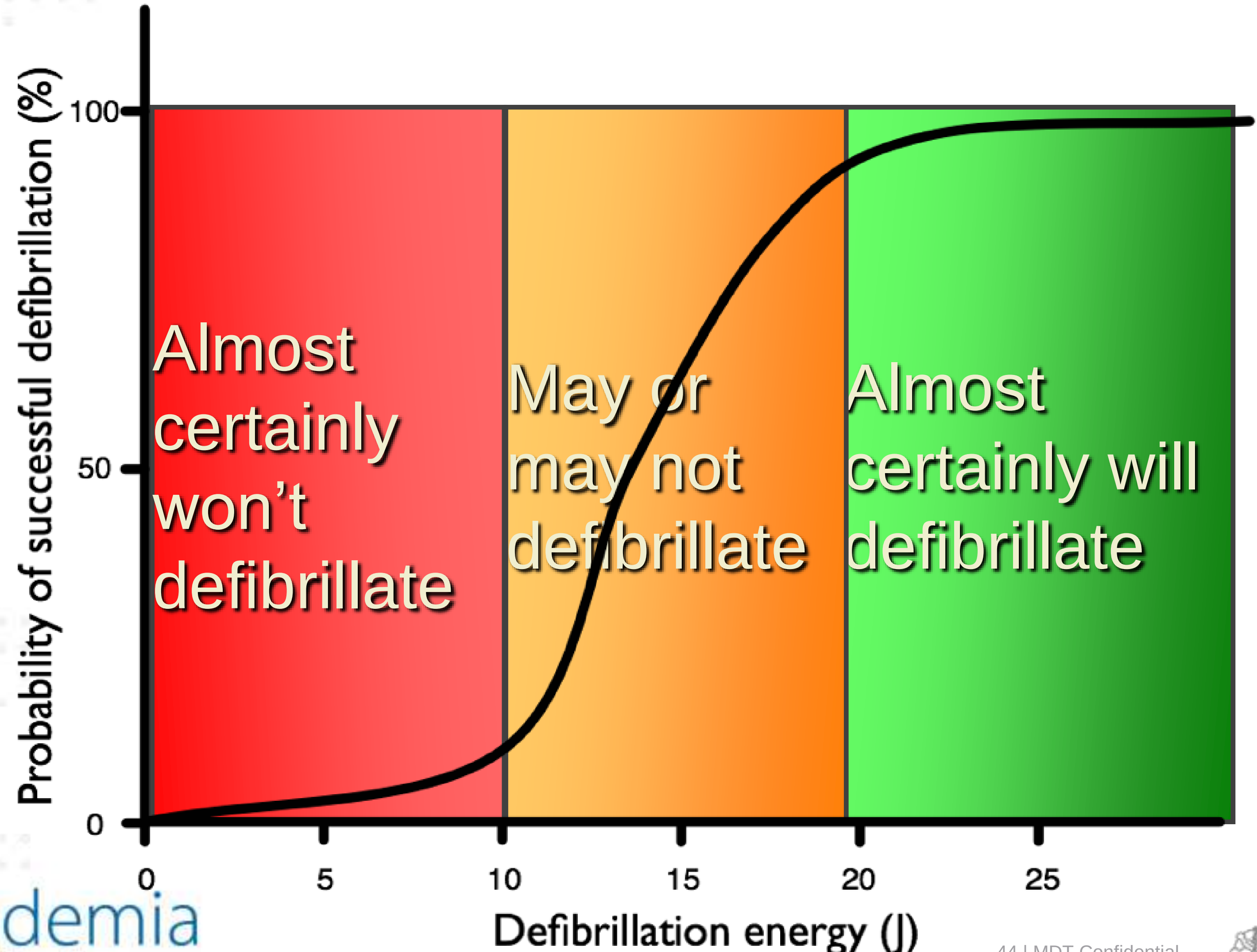
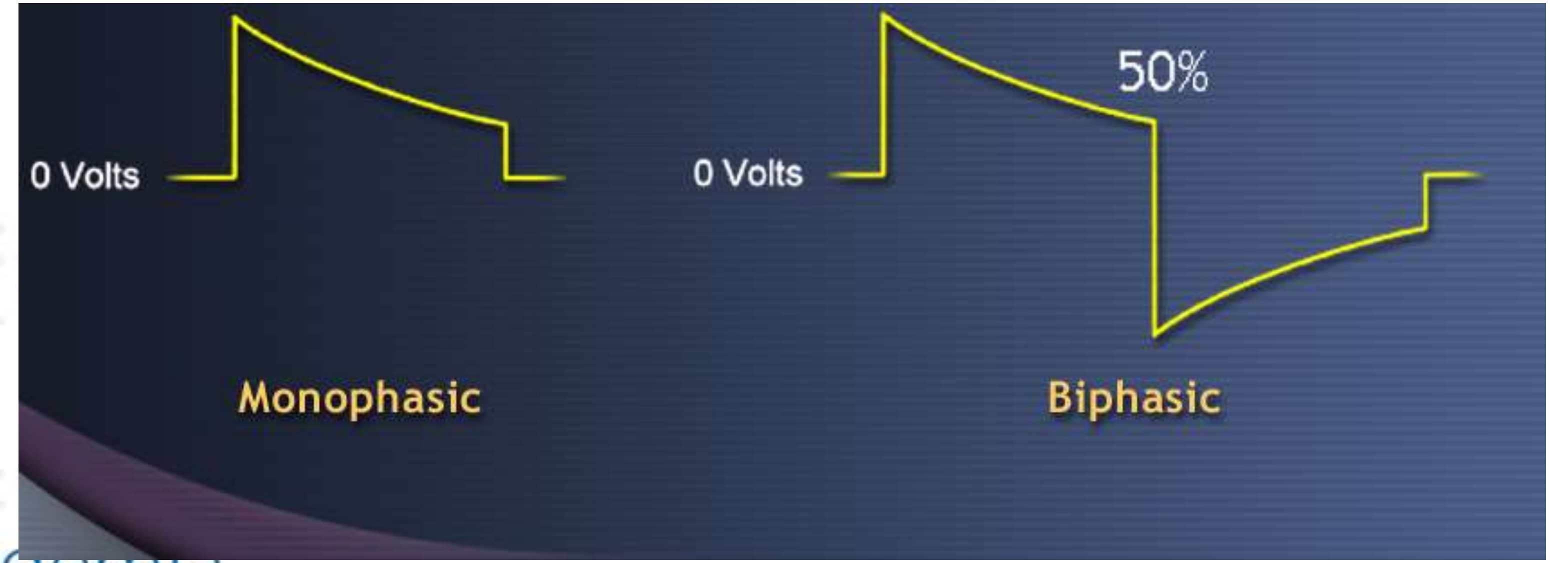
Defibrillation



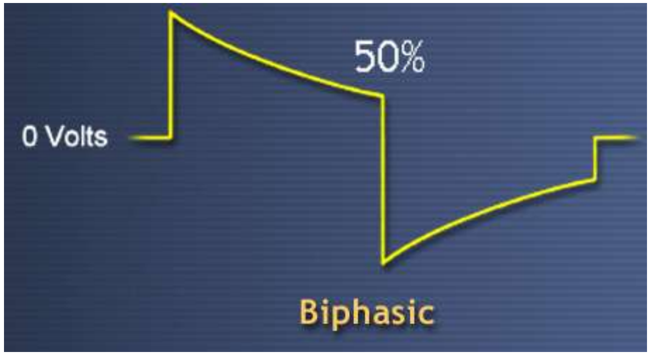
Shock characteristic

- Other Considerations:
  - **Shock delivery waveform**
    - **Monophasic – energy flows in one direction during discharge**
    - **Biphasic – energy reverses direction during discharge**



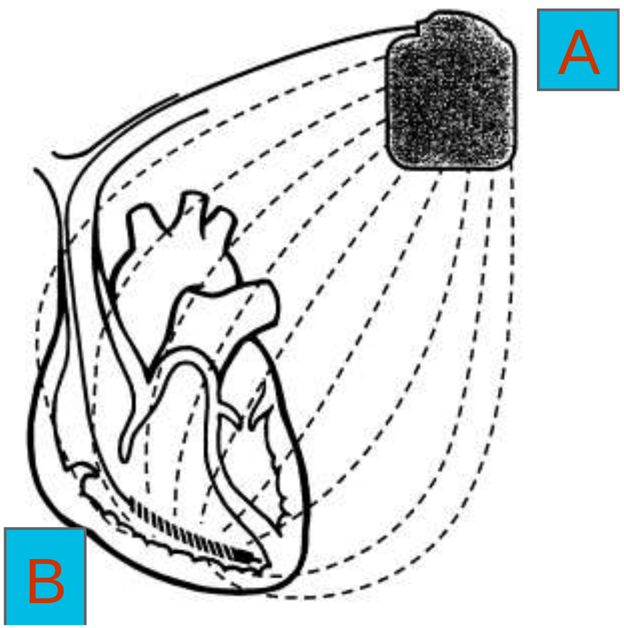
Biphasic Shock

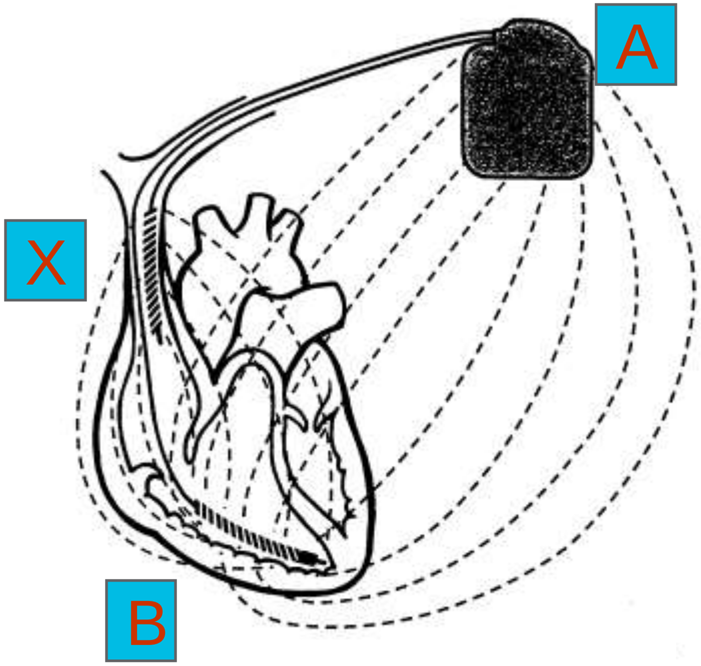
- Lower defibrillation thresholds
- Higher implant success rates
- Reduced short-term myocardial injury
- Faster return to sinus rhythm post-shock



Shock Vectors

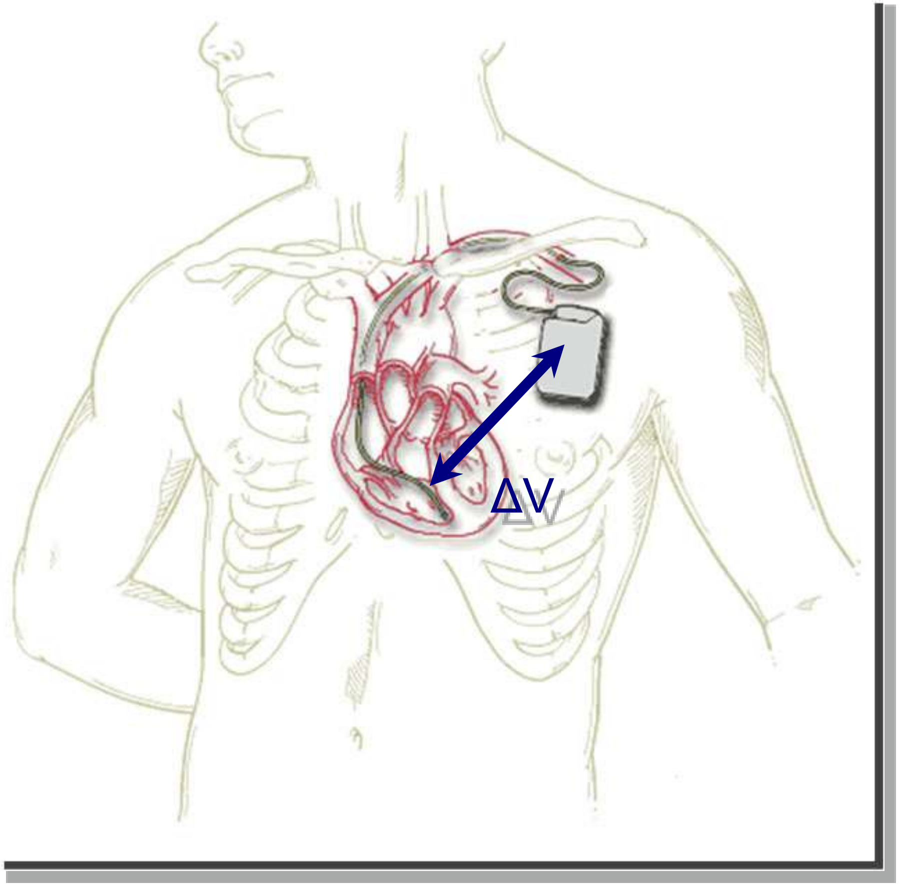
- HVA / HVX to HVB or
- HVB to HVA / HVX





Tissue Impedance

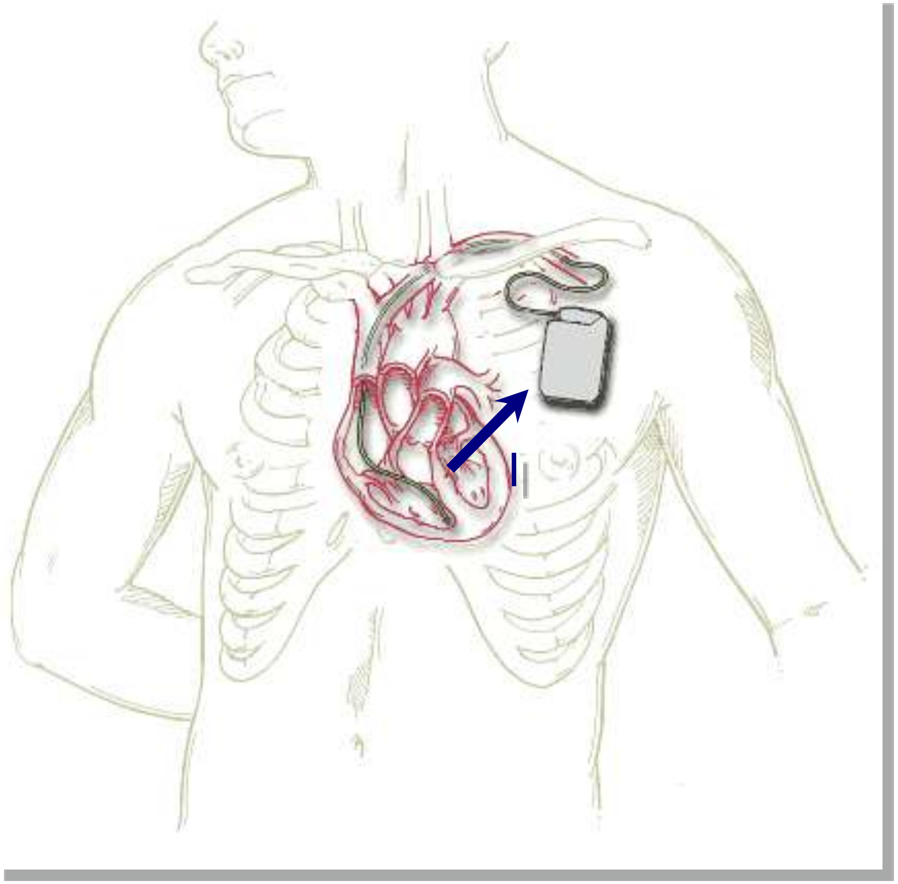
- ICDs have a capacitor system which generates a voltage between the can and the coil



Tissue Impedance

- The voltage gradient results in current flow
- The size of the current depends on the tissue impedance
  - Also known as the “Shock impedance”
  - High impedance- low current
  - Low impedance- high current

- Shock Impedance is smaller then the Pacing Impedance
  - **Range: 50 – 200 Ohms**



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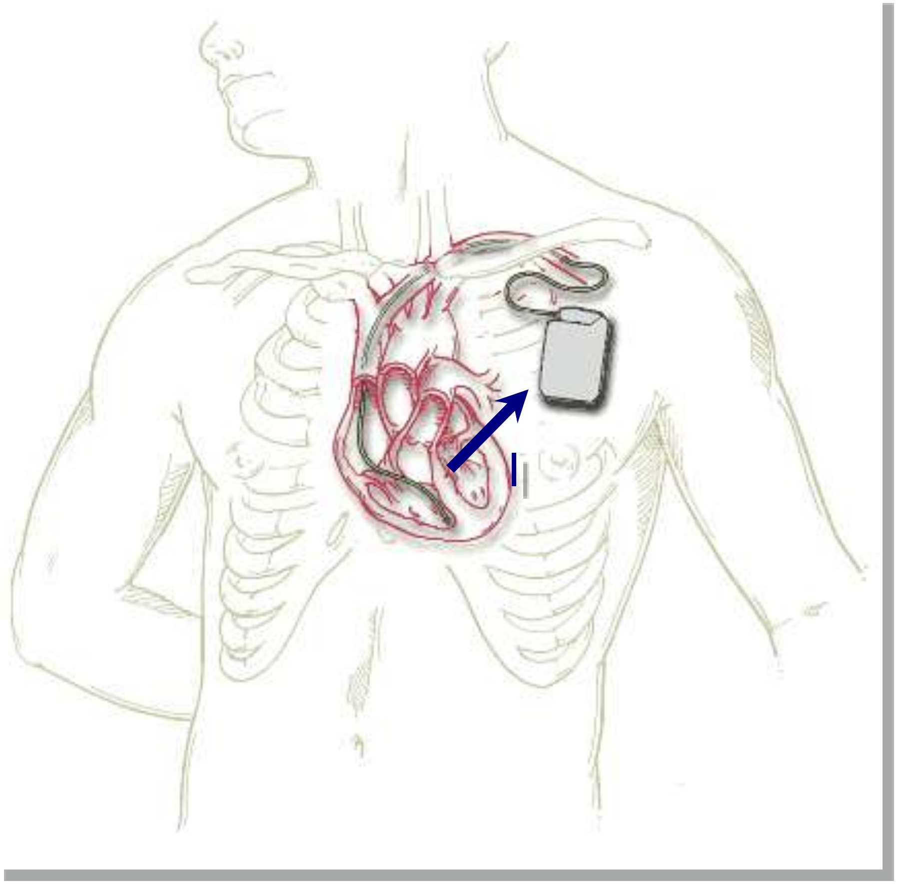
Tissue Impedance

- High impedance will reduce the overall current and may prevent successful defibrillation- e.g.
  - LV dilatation
  - Pneumothorax



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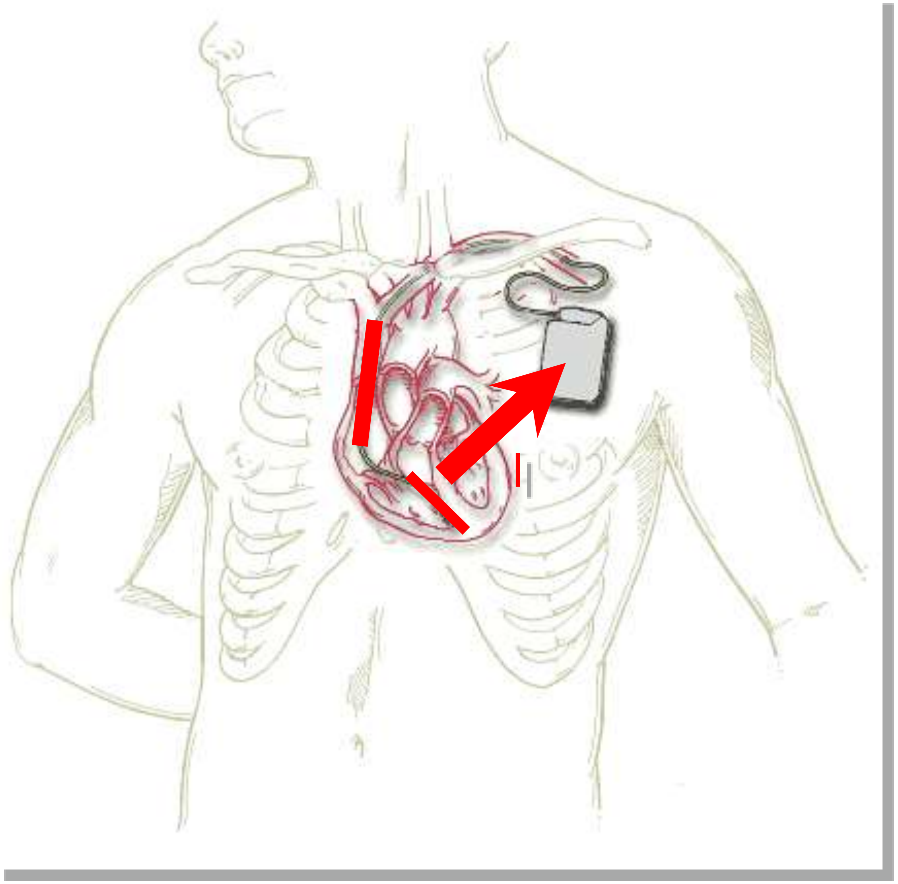
Tissue Impedance

- Additional elements in the circuit can reduce the overall impedance and increase current flow
  - SVC coil
  - SQ array
  - Epicardial patch
- Hence DFT can be lowered



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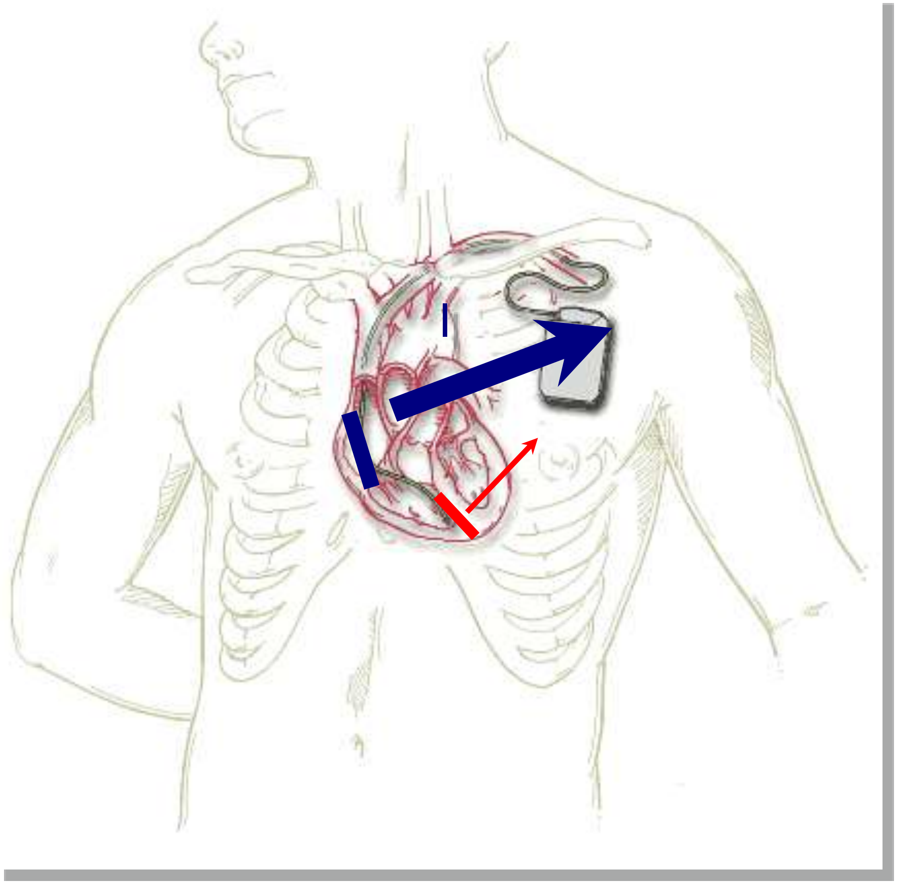
Current shunting

- Additional elements in the circuit may direct current away from the heart
- Impedance may be low and current high but energy never gets to myocardium
- For example
  - SVC coil in RA
  - Retained pacing wires/ stylets



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Thank You

- Any Questions

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