Introduction to Electrical Stimulation

2019/02/07

What you can expect to learn today

- The relationship between stimulus strength and duration
- How current, charge, and energy relate to stimulation thresholds
- How the stimulation threshold is modeled and what changes it.
- Considerations when applying currents and voltages to volume conductors
- *Uniform electric field stimulation*

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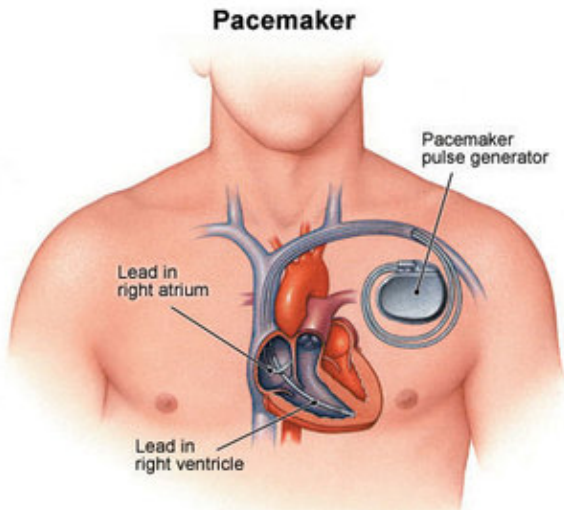

The Strength-Duration Curve and Its Importance in Pacing Efficiency: A Study of 325 Pacing Leads in 229 Patients

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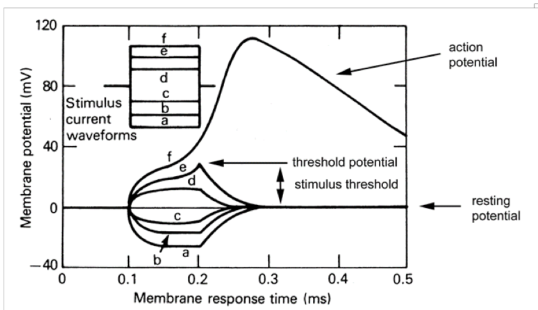
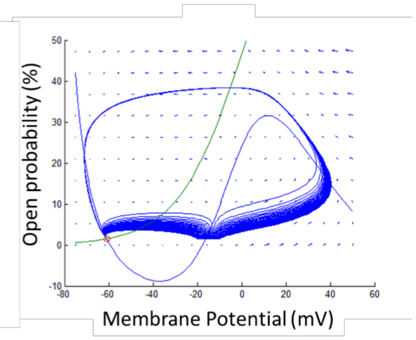
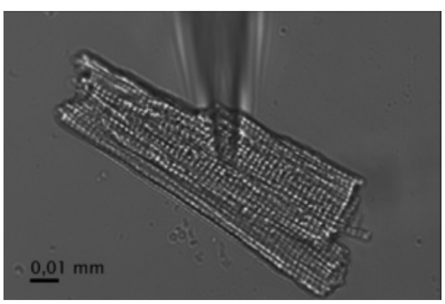
COATES, S., ET AL.: The Strength-Duration Curve and its Importance in Pacing Efficiency: A Study of 325 Pacing Leads in 229 Patients. *Pacemaker battery life is dependant on programmable parameters, principally pulse amplitude and pulse duration. High factory default settings cause excessive current 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)*

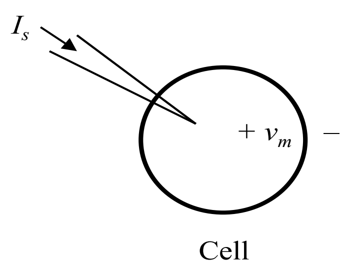
Simple threshold behavior



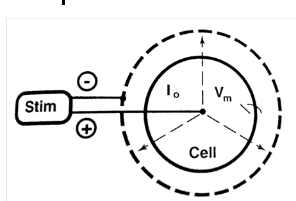


Insights from single cells

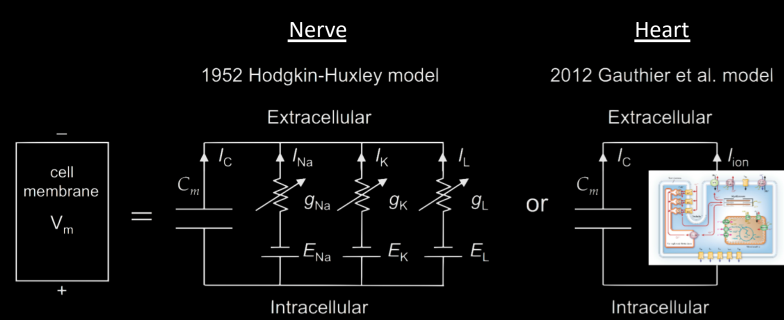


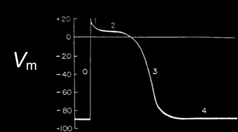


The isopotential assumption



Ionic Currents Give Rise to the Action Potential





$$I_C = C_m \frac{\partial V_m}{\partial t} = -(I_{Na} + I_K + I_L)$$

$$\Rightarrow \frac{\partial V_m}{\partial t} = -\frac{1}{C_m}(I_{Na} + I_K + I_L)$$

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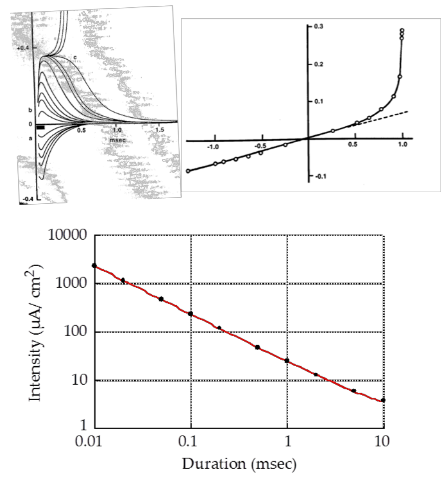
How are current, charge, and energy related?

- **Current** density through the electrode determines the electric field, which drives changes in transmembrane potential. It would be desirable to limit this parameter to minimize possible injury effects to the tissue.
- **Charge** is related to the storage capacity of the battery (usually expressed in Amp-hours, Ah), and it would be desirable to minimize this parameter to extend the number of shocks possible.
- **Energy** (in J) is often used to characterize the strength of pulses applied during defibrillation and is a function of pulse voltage and tissue resistance. The pain of defibrillation shocks is also related to the energy delivered. The capacity of batteries is sometimes expressed as energy density, either in J/kg or J/cm3. It is usually desirable to minimize this parameter to minimize possible injury effects to the tissue and to reduce pain.

Predictive value?

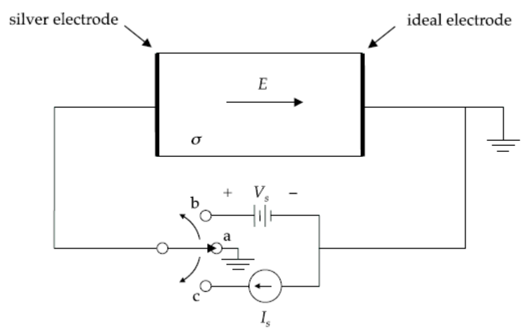
- We assumed the simple RC dynamics were valid up to a static "threshold" value
- A fixed threshold doesn't account for "accommodation."
- We assumed an intracellular stimulus electrode. In general stimulation is accomplished with an extracellular electrode.



Revisiting the idea of a static threshold

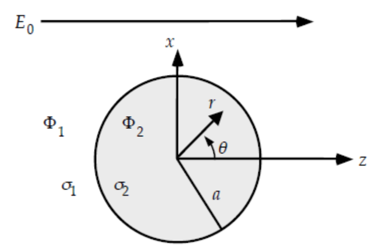
- How does membrane nonlinearity alter the threshold – let's revisit SBE I

Applying voltages and currents in a volume conductor



How do we account for extracellular application of stimulation?

- Assume we apply a field, E_0 to a spherical cell lying in a volume conductor.
- Potentials must satisfy Laplace's equation.
- What boundary conditions can we use to solve for the potentials inside and outside the sphere?



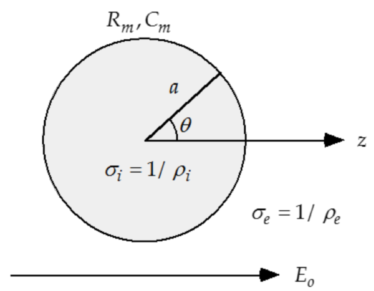
$$\nabla^2\Phi = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2\frac{\partial\Phi}{\partial r}\right) + \frac{1}{r^2\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial\Phi}{\partial\theta}\right) + \frac{1}{r^2\sin^2\theta}\frac{\partial^2\Phi}{\partial\phi^2} = 0.$$

$$\Phi_a = -E_0 r\cos\theta$$

$$\Phi_1 = Ar\cos\theta + \left(\frac{B}{r}\right)^2\cos\theta$$

$$\Phi_2 = Cr\cos\theta + \left(\frac{D}{r}\right)^2\cos\theta$$

Now consider a spherical cell's response



$$v_m = \frac{3\sigma_i\sigma_e R_m E_o a\cos\theta}{a\sigma_i + 2a\sigma_e + 2\sigma_i\sigma_e R_m}\left(1 - e^{-t/\tau'}\right)$$
$$= \frac{R_m}{R_m + R_a}\left(\frac{3}{2}E_o a\cos\theta\right)\left(1 - e^{-t/\tau'}\right)$$

$$\frac{1}{\tau'} = \frac{1}{R_m C_m} + \frac{2\sigma_i\sigma_e}{aC_m(\sigma_i + 2\sigma_e)}$$
$$= \frac{1}{R_m C_m} + \frac{1}{R_a C_m}$$

$$R_a = a(\rho_i + 0.5\rho_e)$$