EN580.435 APPLIED BIOELECTRICAL ENGINEERING Feb. 26, 2019
The Johns Hopkins University

The homework policy for this course is that you are expected to work on the problems on your own. You may collaborate on homework assignments only insofar as group discussion and peer learning. Assignments must be written up individually in each individual's words and NOT COPIED. It is highly recommended that the actual solution of the problem be done by yourself, much like you would do on an exam since the exam will be modelled after the homework questions. If you need further help to understand the problem, you should contact or meet with either Dr. Hunter or Dr. Tung. Homework turned in after the start of class on the due date will receive only 50% credit until noon the next day and only if it is not discussed in class, and 0% after that.

Furthermore, some homework questions given throughout the course may require that you do some research or make some assumptions regarding relevant parameters or other information. Conversely, extra information will sometimes be given that is not needed to solve the problem. You will need to recognize these situations when they come up.

This week Problems 1, 2 and 4 are more conceptual and open ended and, as such, should be completed individually. The intent is for you to consider the concepts we discussed in class in more detail and to communicate your thought process.

Homework #3 (due in class on Mar. 5

Problem 1 (15 pts)

You have been contracted by a medical device company to design an updated lead for biventricular pacing in CRT. They are having problems with extraneous stimulation occurring at the ring electrode of the RV lead and they need you to provide an explanation for what is happening and how to correct it. Their current system uses the **RV tip-to-RV ring and LV tip-to-RV ring locations** discussed in class. For this problem you need to justify your explanation for what is happening at the anode(s)/cathode(s). You should consider both the physiological parameters (e.g. thresholds, tissue conductivities, conduction velocity, scale, etc.), and the physical parameters (e.g. electrode separation, surface area, position, etc.). You can assume that the RV and LV catheters are oriented parallel to the endocardial surfaces (so that the tip and ring electrodes are both in contact with the tissue). It may be helpful to reference literature to justify your reasoning.

a. Give a plausible explanation for why they are seeing stimulation from the RV ring even when they are not pacing the RV. Is this excitation likely due to make or break excitation?
b. To synchronize the ventricles the RV and LV need to be paced at different times. When the delay between RV and LV stimuli (RV-LV delay) is at just the right value they noted that arrhythmia was consistently initiated. This was obviously concerning, and they need to understand why this happens. What was likely causing this initiation of arrhythmia? Hint: What effect would increasing the distance between the RV tip and ring have on the RV-LV delay that causes arrhythmia?

c. What simple change can they make to their catheters to eliminate this issue of extraneous stimulation from part (a)? Hint: this can be done without relocating any of the electrodes.

Problem 2 (15 pts)

In class we discussed ATP as a therapy that can be used for monomorphic VT. The standard in clinical practice is to calculate the cycle length (CL) of VT and then apply at least 8 pulses at ~88% the calculated CL.

a. If the goal is to slow down the arrhythmia (since it's a tachycardia) why is the standard to pace faster? Why is there a minimum number of pulses that should be applied?
b. Suppose you desire to improve upon this clinical standard by modifying the protocol. Use the techniques we've covered (measurement, stimulation, and physiology) to propose a better plan. There is no one right answer for this question, and it should be answered individually (no collaboration with classmates). As in our class discussion of pacemaker algorithms, you should carefully specify where and when you would sense and pace.

Problem 3 (15 pts)

Ablation is a procedure in which a catheter is used to burn a region of tissue to terminate arrhythmias. Assume for this problem that an ablation catheter is modeled as a current source at a point in an infinite volume conductor. The current source has a magnitude, I, and you keep it on for a duration, d. The volume conductor has resistivity ρ=50 Ω-cm, and the volumetric heat capacity of the medium is $4.2\,\frac{J}{cm^3{}^\circ C}$

a. Assume that you are interested in what happens in a spherical volume around the ablation catheter with radius, r. Solve for the current density at the surface of the sphere. Your answer should be in general terms (i.e. no need for specific values of I, d, and r).
b. Determine the power dissipated between the surface of the sphere (at r) and $r+\delta$, where δ is a small distance that defines a spherical shell. You can assume that δ is small enough that the current density is constant between r and $r+\delta$. Your answer should be in W/cm^3.
c. Determine the change in temperature from baseline for the volume between r and $r+\delta$.
d. Now assume that after quick application of the ablation current a spherical ring of charred tissue has developed between $r/4$ (the surface of the electrode) and $r/2$. How would this impact the result from part (c)? You do not need to solve this problem, but thinking through how you would solve it may be instructive.
e. Suppose it is known that charring near the electrode results in limited lesion formation. Does your explanation in part (d) support this? Why or why not?

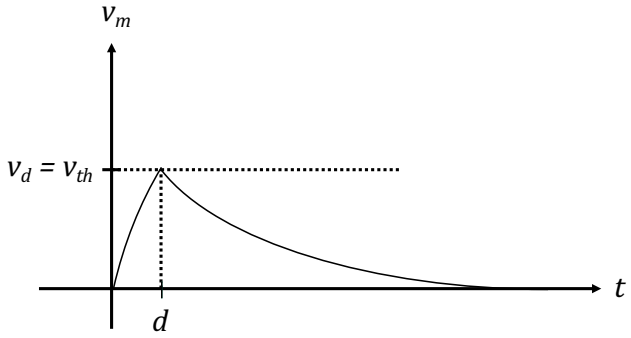
Problem 4 (20 pts)

The WalkAide and Ness L300 are two devices that have been marketed to treat foot drop. Suppose you have a relative with this health problem and would like to find out whether their medical insurance would pay for them. First, what are the costs of these devices? Second, find out what you can about medical reimbursements by different insurance plans, and whether they cover these particular devices. This problem will be graded according to how thorough you research this problem (your answer should be limited to one to two pages, double spaced, and can include citations to references/web links, etc).

Problem 5 (15 pts) extra credit for 580.435; required for 580.635

In Handout #4 on Electrical Stimulation, a derivation was presented for the strength-duration relation of a cell based on the passive charging of an RC circuit up to a threshold voltage. An unrealistic prediction of this relation is that arbitrarily short pulses are still capable of exciting the cell provided that the amplitude of the pulse is sufficiently large. However, this scenario fails to take into account several factors. First, the inward sodium current, which is responsible for the action potential upstroke, has an activation time which cannot be arbitrarily short. Second, with large transmembrane depolarization, the membrane resistance falls as ion channels become activated, resulting in a smaller than expected depolarization. In this problem, we address the first limitation, using a simplified model.

Assume that the membrane time constant τ is, say 10 ms. The membrane response to a short, say d = 1 ms, rectangular stimulus pulse looks like,

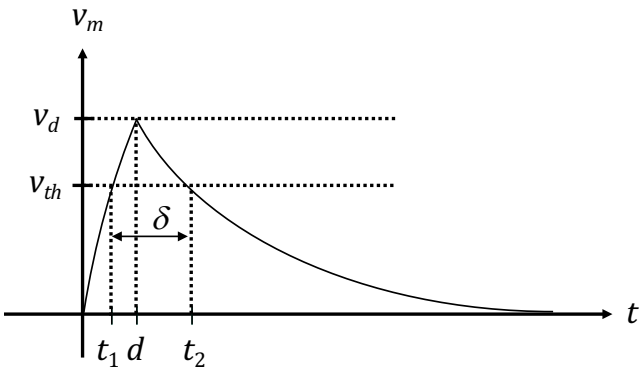


where v_d is the voltage at the end of the stimulus pulse. In Handout #4, we assumed that if v_d reaches a threshold voltage v_{th}, the membrane will fire an action potential. This results in the following strength-duration equation:

$$I = A\left(\frac{v_{th}}{R_m}\right)\left(\frac{1}{1-e^{-d/\tau_m}}\right) \qquad (1)$$

where A is the total membrane area of the cell, d is the pulse duration, and I is the total current at threshold, in units of pA. Suppose we now add an additional constraint, that v_m

must *exceed* v_{th} *for some minimal period of time* equal to say, 1.5 ms, or more generally, δ ms. That results in a response that looks like:



(a) Derive an expression for the new strength-duration relation. It should take the form,

$$I = A\left(\frac{v_{th}}{R_m}\right)\left(\frac{1}{1-e^{-d/\tau_m}}\right) + f(A, v_{th}, R_m, d, \tau_m, \delta) \qquad (2)$$

where there is an additional term on the right-hand side that is a function of the indicated variables. Your answer should reduce to Eq. 1 when $\delta = 0$.

(b) Plot out Eq. 2 under this new scenario with $\delta = 1.5$ ms ($0 < d < 10$ ms), and on the same graph, plot out the strength-duration relation given by Eq. 1. Also plot out the two equations on an expanded scale ($0 < d < 4$ ms, $0 < I < 2000$ pA) to facilitate comparison. Assume that $R_m = 10$ kΩ-cm^2, $v_{th} = 25$ mV, and that the cell is spherical with radius 10 μm.

(c) If for example, $\delta = 1.5$ ms (i.e., v_m must exceed v_{th} for at least 1.5 ms in order for the sodium channel to activate), how is it possible that a pulse having only a 1 ms duration (d = 1 ms) can stimulate?

(d) If $\delta = 1.5$ ms, how much of an increase is there in the stimulation threshold at d = 1ms compared to the case where there is no limit as to how fast the sodium channel can activate?