ECE 366/566 - Neural Engineering & Implantable Devices

End-Sem Exam – Set B

Total points: 60 May 4, 2024

Instructions

- There are 15 multiple-choice questions. **[Question 1]**
  - Each question carries 1 point.
  - Some questions have multiple choice correct. It is clearly specified in the question if it has multiple choices correct. There is a negative marking for these questions. Incorrect choices will be penalized in the same proportion as the reward for correct choices.
  - Rest MCQs have precisely one correct choice. There is no negative marking for these questions.
  - If your total marks in Question 1 are negative, it will be made 0.
- There are 3 medium-answer questions. **[Questions 2, 3, and 4]**
  - Each question carries 5 points.
  - For these questions, provide asked explanations, calculations, and justifications.
- There are 3 long-answer questions. **[Questions 5, 6, and 7]**
  - Each question carries 10 points.
  - For these questions, provide asked explanations, calculations, and justifications.
- If a parameter is missing in a question, use an appropriate value with proper justification.
- Please clearly mention the question numbers for which you are writing the answer.
- **Please write your set in the answer sheet.**

Na^+

Question 1 [15 points] K^+

1. [CO1] Which of the following is true? Mark all correct choices.
   (a) There are fewer potassium ions in the neuron's exterior than in the interior. That is why the reversal potential for potassium ions is negative.
   (b) There are fewer sodium ions in the neuron's exterior than in the interior. That is why the reversal potential for sodium ions is negative.
   (c) For most neurons at rest, the membrane is more permeable to potassium ions. Therefore, the resting state membrane potential is negative.
   (d) For most neurons at rest, the membrane is more permeable to sodium ions. Therefore, the resting state membrane potential is negative.
2. [CO4] Which of Maxwell's equations is the magnetic stimulation based on?
   (a) Gauss's law for magnetism
   (b) Ampere's circuital law
   (c) Biot-Savart law
   (d) Faraday's law of induction
3. [CO3] The very first brain signal recording was performed using
   (a) Intracortical electrodes
   (b) Magnetic resonance imaging
   (c) Microelectrode arrays
   (d) Scalp electrodes
4. [CO1] Neural spikes are "all or none". What does this mean? Multiple choices could be correct.
   (a) Neural spikes can be considered a digital signal. Spike trains are basically a stream of 1 and 0.
   (b) A neuron generates a smaller spike if the stimulation is subthreshold.
   (c) All spikes generated by a specific neuron have the same shapes and amplitudes.
   (d) Two neurons with different ion channel properties will still generate spikes of the same shape.
5. [CO3, CO4] Which of the following techniques can be used to record local field potentials (LFPs)?
   (a) Electrocorticography (b) fMRI (c) Electroencephalography (d) Microelectrode array

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6. [CO3, CO4] Which of the following is true for different biological tissues? Multiple choices could be correct. σ is electrical conductivity and μ is magnetic permeability.
(a) σ varies significantly
(b) μ varies significantly
(c) σ is almost the same
(d) μ is almost the same

7. [CO1] Synapses send information from
(a) Postsynaptic neuron's dendrite to presynaptic neuron's axon terminal
(b) Presynaptic neuron's dendrite to postsynaptic neuron's axon terminal
(c) Presynaptic neuron's axon terminal to postsynaptic neuron's dendrite
(d) Postsynaptic neuron's axon terminal to presynaptic neuron's dendrite

8. [CO4] Figure-of-eight coils are used in transcranial magnetic stimulation system because
(a) It has a wider distribution of E field
(b) It has a localized distribution of E field
(c) It has a higher stimulation threshold
(d) It has lower energy recovery efficiency

9. [CO1, CO2] Consider a squid giant axon. If all m gates of the sodium channels stop working, how would it impact the action potential shape? Spike will be ________
(a) Narrower
(b) Smaller
(c) Smaller and narrower
(d) Absent

10. [CO1, CO4] Consider two neurons: neuron A1 and neuron A2. Neuron A2 is the same as A1, but its axon has a double diameter compared to that of neuron A1. Multiple choices could be correct.
(a) Spike propagation can happen from the axon to the soma during electrical stimulation.
(b) When activated using electrical stimulation, A1 will have a lower stimulation threshold.
(c) When activated using electrical stimulation, A1 will have a higher stimulation threshold.
(d) when activated using natural synaptic inputs, A1 will require higher intracellular current input.

11. [CO3] Which of the following primarily contributes to the electric fields recorded by EEG?
(a) Action potentials of pyramidal cells orientated tangentially to the scalp.
(b) Action potentials of pyramidal cells orientated vertically to the scalp.
(c) Post-synaptic potentials of pyramidal cells orientated tangentially to the scalp.
(d) Post-synaptic potentials of pyramidal cells orientated vertically to the scalp.

12. [CO2] You are modeling a neuron using a leaky integrate-and-fire model. How will you increase spiking frequency (rate at which neurons generate spikes)? Multiple choices could be correct. (Reset voltage is the voltage that is enforced just after the spike.)
(a) Reduce reset voltage
(b) Reduce threshold voltage
(c) Decrease $R_m C_m$
(d) Increase $R_m C_m$

$C = \frac{\epsilon A}{d}$

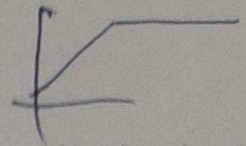
13. [CO1] Which of the following(s) is true regarding myelinated axons?
(a) In myelinated axons, conduction velocity is lower than unmyelinated axons.
(b) In myelinated axons, myelinated sections have lower membrane capacitance.
(c) Sodium and potassium ion channels are present in the myelinated sections.
(d) Myelinated sections of axons are excitable and produce action potentials.

14. [CO1, CO3] Which of the following have the correct order for the amplitudes for a typical post-synaptic potential (PSP), action potential, ERP, and EEG signals?
(a) 100 mV, 10 mV, 5 μV, 100 μV
(b) 10 mV, 100 mV, 5 mV, 100 mV
(c) 10 mV, 100 mV, 5 μV, 100 μV
(d) 100 mV, 10 mV, 5 mV, 100 mV

15. [CO1, CO4] Analog to digital signal conversion occurs at which retinal neurons? AC: amacrine cells, BC: bipolar cells, GC: ganglion cells, PR: photoreceptors.
(a) AC
(b) BC
(c) PR
(d) GC

Question 2 [5 points]

[CO3] Consider a P300-based BCI speller.
(a) Why is ERP (event-related potential) generated by the oddball paradigm called "P300"? [1 point]
(b) Assume you are designing a P300-based BCI Speller using EEG signals. Draw a block diagram specifying all components of this BCI. Explain the function of each component briefly. [2 points]



(c) Can you redesign this BCI speller using the ECoG signals? If yes, what could be the advantages and challenges? If no, explain why. [2 points]

Question 3 [5 points]

[CO1, CO2] Consider two hypothetical spherical neurons, Neuron A (radius 11.28 μm) and Neuron B (radius 5.64 μm). Both neurons do not have any passive or active ion channels. Neuron B has a membrane thickness 1/4 times that of neuron A. Assume a resting membrane potential of -70 mV and membrane capacitance of 1μF/cm2 for neuron A.

(a) What will be the total capacitance (also known as input capacitance) of neuron A? [1 point]

(b) If a step current of 1 nA amplitude and 1 ms duration is injected inside neuron A, what would be the steady-state transmembrane potential of neuron A? [2 points]

(c) What would be the membrane capacitance (specific membrane capacitance) of neuron B? [1 point]

(d) What would be the total capacitance of neuron B? [1 point]

Question 4 [5 points]

[CO1, CO2] In the Hodgkin & Huxley model, the following equation represents the sodium current.

$$i_{Na} = \overline{g_{Na}}\, m^3 h\, (V_m - E_{Na})$$

(a) During an action potential, which quantities of this equation remain constant? Which quantities are a function of time? Which quantities are a function of transmembrane potential and time? [2 points]

(b) What do rate constants (α and β) signify? Draw a plot of α_h and β_h with respect to transmembrane potential. [1 point]

Suppose the maximum conductance $\overline{g_{Na}}$ is doubled.

(c) How would it impact the shape of the action potential? Why? [1 point]

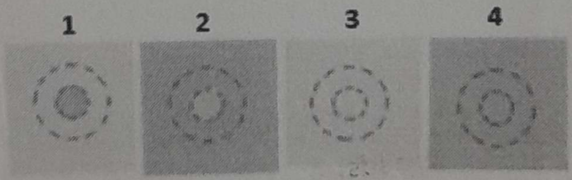
(d) How would it impact the conduction velocity of the spike? Why? [1 point]

Question 5 [10 points]

[CO1, CO3, CO4] Answer the following questions for a healthy retina.

(a) List all the retinal cells that exhibit center-surround receptive fields in a healthy retina. How do these cells get center-surround receptive fields? [1 point]

(b) Which light stimuli would lead to the highest spiking rate in the healthy on-type retinal gangiion cells? [1 point]



Consider Retinitis Pigmentosa (RP), a retinal degenerative disease. The photoreceptors are completely destroyed at the considered disease stage; however, ganglion cells are mostly intact. Suppose you are designing an epiretinal prosthetic system for the treatment of RP.

(c) Provide an advantage and a disadvantage of epiretinal implants over subretinal implants. [1 point]

(d) Assuming you have electrodes of varying sizes. How would you arrange these varying-sized electrodes in the retinal implant electrode array? Justify your answer. [2 points]

(e) What are the constraints on the pulse width size of the stimulation current waveform? What sets a limit on the minimum possible pulse width? What sets a limit on the maximum possible pulse width? [2 points]

(f) Suppose you cannot make electrodes smaller. Suggest and explain a strategy to improve the spatial resolution of epiretinal implants. [1 point]

(g) What modifications will you make in this visual prosthetic system to make it suitable for Glaucoma patients with damaged optic nerves? What are the advantages and design challenges for this modified visual prosthetic system? [2 points]

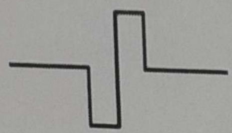
Question 6 [10 points]

[CO3, CO4] Suppose you are working in a research team to design an electrical stimulation system for the sciatic nerve. Your first task is to design a stimulation current waveform that is safe and effective.

(a) Assume you are using a planar disc electrode (diameter is 0.5 nm) with a charge-balanced biphasic current waveform (each phase is 1 ms), as shown below. To ensure no neural damage ($k \leq 1.5$), what will be the maximum current for the stimulation waveform design? [2 points]

(b) What is the role of the second phase in a biphasic current waveform? [1 point]

(c) While testing your current waveform during the in-vivo experiments, you realized that the nerve fibers do not generate spikes. Staying within the safety limits, you tried increasing the stimulation current amplitude and phase width, but that did not help. Next, you tried using a monophasic current waveform, which worked perfectly. However, you don't want to use monophasic current waveform for safety reasons. How will you modify the stimulation waveform? Provide proper justification for your answer. [2 points]



Your second task is to use the most efficient electrode designs for this electrical stimulation system. Suppose you have three electrodes available:

E1: a MEMS-based microelectrode array with thin needle electrodes (with tip diameter in µm).

E2: a relatively much larger planar disc electrode (diameter in cm).

E3: an electrode made of Ag/AgCl with a small surface area (diameter in mm). For the Ag/AgCl electrode, a very minimal change in voltage across the electrode-tissue interface occurs as the current flows through it.

(d) Which of these electrodes will you use as a stimulating electrode? Justify your choice. [1 point]

(e) Which of these electrodes will you use as a ground electrode? Justify your choice. [2 points]

(f) Which of these electrodes will you use as a reference electrode for the electrode impedance measurement? Justify your choice. [2 points]

Question 7 [10 points]

[CO4] Consider a resonant inductive coupling-based wireless power transfer system.

(a) Write the Z-parameters matrix for the 3-coil WPT system. Using the determinant of the Z-matrix, extract the expressions for reflected impedances. Derive the expressions of reflected impedances in terms of quality factors. [3 points]

Assume you are designing an efficient 3-coil wireless power transfer (WPT) system for a neural implant. You have three mm-sized solenoid coils. Coils A have 20 µH inductance and 1 Ω resistance. Coils B have 10 µH inductance and 2 Ω resistance. Coils C have 20 µH inductance and 4 Ω resistance. Coil B has 10 times fewer turns than Coil C. The load and source resistance are both 100 Ω. Assume 10 MHz as the frequency of operation.

(b) Which among coils, A, B, and C, will you use as the receiver coil? Which of these will you use as the load coil and transmitter coil? Justify your choices. [3 points]

(c) Calculate the power transfer efficiency of this 3-coil WPT system. Assume k12 is 0.1 and k23 is 0.3. [2 points]

(d) Calculate the power transfer efficiency if the middle coil is removed. The k12 is still 0.1. [2 points]

$$\eta_{2-coil} = \frac{R_L}{R_L + R_2}\left(\frac{k_{12}^2 Q_1 Q_2}{1 + k_{12}^2 Q_1 Q_2}\right); \qquad \eta_{3-coil} = \frac{R_L}{R_L + R_3}\left(\frac{k_{23}^2 Q_2 Q_3}{1 + k_{23}^2 Q_2 Q_3}\right)\left(\frac{k_{12}^2 Q_1 Q_2}{1 + k_{12}^2 Q_1 Q_2 + k_{23}^2 Q_2 Q_3}\right)$$