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Basic Neuron Model Electrical Equivalent Circuit: An Undergraduate Laboratory Exercise

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We developed a hands-on laboratory exercise for undergraduate students in which they can build and manipulate a neuron equivalent circuit. This exercise uses electrical circuit components that resemble neuron components and are easy to construct. We describe the methods for creating the equivalent circuit and how to observe different neuron properties through altering the structure of the equivalent circuit. We explain how this hands-on laboratory activity allows for the better understanding of this fundamental neuroscience concept.

At the conclusion of this laboratory exercise, undergraduate students will be able to apply the principles of Ohm's law, cable theory with regards to neurons, and understand the functions of resistance and capacitance in a neuron.

Key words: Ohm's Law, RC Circuit, cable theory, electrical equivalent circuit, neuron model, electrical properties

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Interactive laboratory exercises provide students with hands-on experience, encourage critical thinking, and facilitate topic comprehension. Biophysical properties of neurons are often difficult for students to visualize with lecture alone, making this topic particularly well-suited for the application of an interactive laboratory activity. Since properties of resistance, capacitance, and passive conductance are often described using cable theory (Rall, 1960), a simple RC circuit can be created to describe the electrical properties of neurons to show the current flow and time constant of the neuron (Koch, 1999). Here, we provide details on how a neuron electrical equivalent circuit can be easily created and manipulated by students using inexpensive and readily available components.

RC Circuit: Representation of capacitance
The membrane of a neuron is often related to a capacitor because of its ability to store and separate a charge (Squire et al., 2008). In an electrical circuit, a capacitor possesses two conducting regions with a separation of non-conducting material in between. When one conducting region accumulates a charge, an electric field is created, which pushes the charge off of the subsequent conducting region of the capacitor. This phenomenon only lasts a short amount of time, producing a brief current which is expressed as: $I = C\,dV/dt$, where I represents the current, C represents the capacitance, and dV/dt represents the rate of voltage change with time (Squire et al., 2008). In a neuron, the conducting regions of the capacitor are represented by the conductive intracellular and extracellular solutions of the cell. The non-conducting insulator of the capacitor represents the non-conducting membrane of the neuron.

RC Circuit: Representation of resistance
In a neuron, ion channels allow current to flow in and out of the cell (Squire et al., 2008). When more ion channels are open, more ions are able to flow. This represents a decreased resistance, which leads to an increase in conductance. As passive transports, ion channels can be represented with resistors in an RC circuit. The amount of current flowing through these resistors can be expressed by Ohm's Law: $I = V/R$, where I represents the current, V represents the voltage, and R represents the resistance (Ohm, 1827).

RC Circuit: Representation of concentration gradients
The concentration gradient of a neuron is the external to internal ratio of ion concentration, and can be represented with a battery in this RC circuit (Kandel et al., 2012). The battery symbolizes the overall differences in ion concentration inside and outside of the cell (more positive and more negative) that generate (resting) voltage for possible current flow. For simplicity, the resting voltage is excluded from Figure 1.
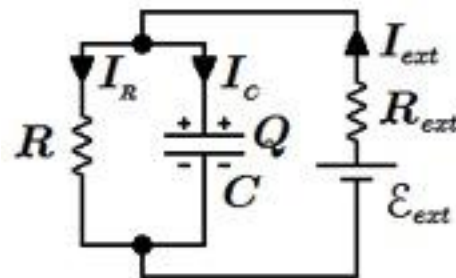

Figure 1. Effective electrical circuit for the basic neuron model.

RC Circuit: Putting it all together
With these components – resistors, capacitors, and a battery – current flow in a neuron can be emulated (Figure 1). The time constant, can be calculated: $\tau = RC$, where τ represents the time constant, R represents the resistance, and C represents the capacitance (Liptak, 2003). The time

constant governs the time it takes to reach a steady state response after a change in the voltage across a membrane. In both a neuron and an electrical circuit, this voltage rises to the steady state level asymptotically in the response to an external current (e.g., from an action potential). Once the external current is shut off, the voltage drops in a similar asymptotic way (Figure 2). These characteristics of the membrane voltage can be measured with a simple voltmeter in the RC circuit. Opening more ion channels (or resistors, as in this RC circuit), which decreases resistance and increases conductance, will express a more rapid increase in voltage on the voltmeter, visually demonstrating the properties of resistance in a neuron.

Building on the fundamental classroom concepts of neuron resistance and capacitance, this undergraduate laboratory exercise allows students to build and manipulate a basic working circuit representation of the biophysical properties of a neuron.
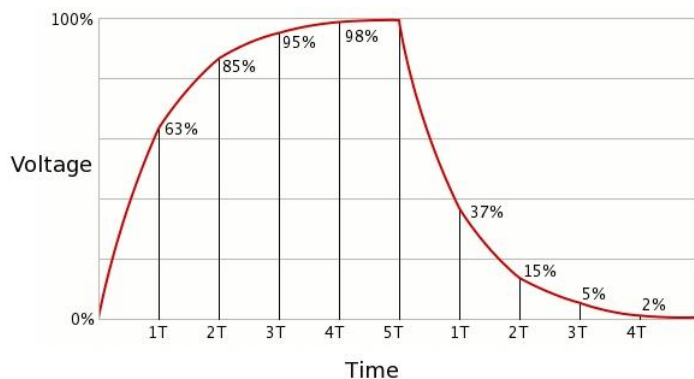

Figure 2. General characteristics of voltage over time in both an electrical circuit and in a neuron.

LEARNING OBJECTIVES

After completion of the experiment, students should be able to:

1. Demonstrate a fundamental understanding of Ohm's Law and its applications to resistance in a neuron.
2. Describe the properties of resistance and capacitance in terms of both an electrical circuit and a neuron.
3. Show how opening ion channels (unclamping one alligator clip from a resistor) speeds up conductance due to decreased resistance, as seen on the voltmeter.
4. Explain how the capacitor is necessary for the asymptotic voltage rise in a neuron.
5. Describe how the neuron's resistance and capacitance affects the time constant.

MATERIALS AND METHODS

Materials

This experiment requires the use of the following components:

- One 6-volt lantern battery (e.g., UltraLast, RadioShack 23-682) to generate an external current.

- One analog voltmeter (e.g., Parts-Express.com 320-235) to display the rise and drop in voltage.
- One 100 microfarad 100 volt non-polarized capacitor (e.g., Parts-Express.com, 027-360) to represent the capacitance of the membrane.
- Two 100k Ohm resistors (e.g., Parts-Express.com 003-100K) to represent two passive transport ion channels.
- Nine alligator clips to connect the components (e.g., Parts-Express.com 099-225). Note that the activity is facilitated by pre-labeling the cables "1-9" ahead of time.

Procedures

Each student or student group should work at independent lab benches in order to spread out materials. In addition, each student should receive the following instructions and copies of Figures 1-3 for facilitation. Throughout the following steps, refer to Figure 3 for proper placement of each resistor, capacitor, battery, and connecting alligator clips.

1. Discharge all resistors and capacitors by clamping alligator clips on each end before working with them.
2. Connect one end of an alligator clip (1 of 9) to the positive terminal on the 6-volt battery and the other end of the clip to one end of the first resistor.
3. Connect one end of a new alligator clip (2 of 9) to the other side of the first resistor and then to another new alligator clip (3 of 9).
4. Connect 3 of 9 to one end of a second resistor.
5. Add a fourth alligator clip (4 of 9) to the other end of the second resistor; leave the other end of this fourth alligator clip open until step 12.
6. Add a fifth alligator clip (5 of 9) to the connection point between the second and third alligator clip, creating a three-way connection between alligator clips 2, 3, and 5.
7. Connect the other end of this fifth alligator clip to one of the conductive regions of the capacitor.
8. Add a sixth (6 of 9) alligator clip to this same conductive region; now alligator clips 5 and 6 should be connected to this conductive region of the capacitor.
9. Connect the other end of this sixth alligator clip to the voltmeter.
10. On the other conductive region of the capacitor, separated by the non-conductive insulator, connect two more alligator clips (7 and 8 of 9).
11. Connect the seventh alligator clip from this conductive region of the capacitor to the other connection point on the voltmeter, and connect the eighth alligator clip to the previously unclipped other end of the fourth alligator clip.
12. Join a ninth and final (9 of 9) alligator clip at the connection point between clips 4 and 8, making a three-way connection point among clips 4, 8, and 9.
13. Keep the other end of the ninth and final alligator clip unclipped for the time being, as this end acts as the "on" signal for turning on the voltage, once

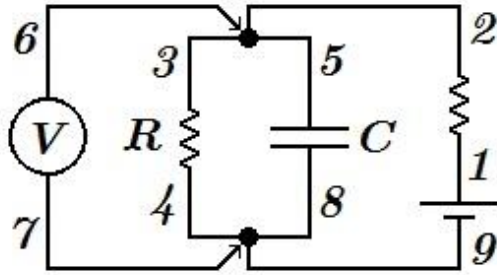clipped to the negative terminal of the 6-volt battery.

Figure 3. Visual depiction of alligator clip connections.

This completes the equivalent circuit. Students should watch their voltmeters as they clip the other end of the ninth alligator clip to the negative terminal of the 6-volt battery. The voltmeter will display the asymptotic – not immediate – rise in voltage. Students do not see a full range of voltage on this meter because the voltmeter is of 10-volts and the battery is a 6-volt battery. Some students may even see a lower range than 6-volts, given that batteries are not always of their labeled voltage. Once students remove the "on" signal (the end of the ninth alligator clip) from the negative terminal of the battery, they can observe a similarly asymptotic drop in voltage.

Manipulating the model: Resistance
Students can open one of the modeled ion channels – in this case, unclip the alligator clamp from one of the sides of a resistor and view the effect that "opening a channel" has on the voltage rise on the voltmeter. They will observe that there will be a more rapid raise in voltage when a channel is open, compared to when a channel is closed. This represents the decreased resistance that accompanies the opening of ion channels.

Students can also add additional resistors and alligator clips to view the increased resistance, and subsequent decreased conductance, with the addition of more ion channels. They are able to observe slower asymptotic rises and drops on the voltmeter in response to these added resistors.

Manipulating the model: Capacitance
Removing the capacitor eliminates the ability of the circuit to store and separate the charge. Students will see that this results in the absence of an asymptotic rise and drop in voltage, as viewed on the voltmeter. Instead, students observe immediate rises and drops in voltages, because the capacitor no longer inhibits the current flow.

Students should not leave the circuit connected for too long, as this can drain the batteries. Once students complete the construction of the circuit and structural alterations to demonstrate changes in current flow, they can simply disconnect the respective parts and alligator clips, all of which are suitable for later use.

DISCUSSION
This laboratory exercise facilitates the comprehension and application of concepts such as Ohm's Law, cable theory,

and the electrical properties of neurons and current flow among undergraduate neuroscience students. These topics can be difficult for students to understand, but comprehending such concepts is essential for further progress in the study of neuroscience. This laboratory exercise provides students with an applicable way to understand how current flows in a neuron, what modulates this flow, and what components are essential for this process.

Existing web-based interactive simulations allow students to manipulate neuron electrical properties (e.g., NEURON, http://www.neuron.yale.edu/neuron/; GENESIS, http://genesis-sim.org/; SPICE, http://bwrcs.eecs.berkeley.edu/Classes/IcBook/SPICE/). The current laboratory activity offers a hands-on, interactive learning experience that can be a meaningful supplement to these web-based tools or serve as a stand-alone learning activity. In the current lab activity, students can physically build an electrical equivalent circuit that represents a neuron and see how changes to the circuit affect subsequent voltage levels (i.e., adding more resistance through increasing the number of resistors, therefore decreasing conductance; opening resistors which represents opening ion channels, therefore decreasing resistance and increasing conductance; removing the capacitor to show the necessity of the property of capacitance in a neuron for optimal voltage rises and drops, etc.). The analog voltmeter allows for a visual way to observe the asymptotic rise and fall of voltages in the circuit, which represents how currents do not immediately reach steady state once a signal is turned on, and immediately drop once the signal is turned off, just like in a neuron.

The simplicity of this circuit allows for neuroscience students of all levels and proficiencies – even the most introductory students – to understand these fundamental concepts of neuron behavior. This laboratory activity is ideal for a small lab group setting at the undergraduate level since it requires minimal parts and is cost-effective (All required parts can purchased for approximately $35.00). Students can receive their own parts and complete the activity at their own pace, with professor facilitation.

In order to show that this lab activity is an effective teaching tool, pre- and post-assessments were administered to evaluate students' knowledge about the electrical properties of neurons (two assessments were used and were counterbalanced). As part of the post-assessments, the students were also asked on a 7 point Likert scale how useful they found this activity in helping them to understand the electrical properties of neurons. Assessment scores significantly increased from pre- (M=.38, SD=.26) to post- (M=.92, SD=.12) assessment; t(13)=-7.27, p<0.01. The average post-activity helpfulness rating was 6.46.

To ensure students accomplish the learning objectives previously delineated, instructors may choose to administer a short quiz. The quiz could consist of questions similar to the following:

1. Describe Ohm's Law and how it relates to

resistance.

2. Identify what the resistor and capacitor of the electrical equivalent circuit represents in a neuron.
3. Describe the curve in which voltage rises and drops.
4. Discuss the changes that result from adding/removing resistors and capacitors from the electrical equivalent circuit.

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