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Bridging Physics and Biology Using Resistance and Axons

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When teaching physics, it is often difficult to get biology-oriented students to see the relevance of physics.[1] A complaint often heard is that biology students are required to take physics for the Medical College Admission Test (MCAT) as part of a "weeding out" process, but that they don't feel like they need physics for biology. Despite this impression held by students, there have been calls for better physics education for future physicians and life scientists.[2,3] Research is being performed to improve physics classes and labs by linking topics in biology and physics.[4,5] Described here is a laboratory experiment covering the topics of resistance of materials and circuits/Kirchhoff's laws in a biology context with their direct application to neurons, axons, and electrical impulse transmission within animals. This experiment will also demonstrate the mechanism believed to cause multiple sclerosis. The apparatus was designed with low-cost and readily available materials in mind.

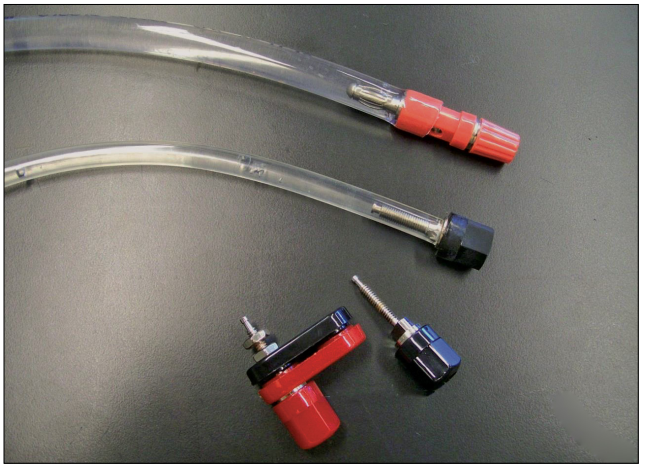

Fig. 2. Photo of 5/16-in tube with binding-post-to-banana-plug (top) and 3/16-in tube with super-glued dual binding post mount (bottom), both filled with salted gelatin.

Neurons and their axons

Neurons are nerve cells that are composed of three major sections, as shown in Fig. 1: the dendrites, the cell body, and the axon. These nerve cells transmit electro-chemical signals to cells such as other neurons, muscles, and endocrine cells. This signal transmission is, for example, how the brain tells muscles to contract. Multiple signals enter the neuron through the dendrites. The separate electrical impulses through these dendrites combine at the cell body. This signal then becomes attenuated as it travels through the cell body toward the axon hillock and is known at this point as the graded potential. This signal reduction is natural since the cell body is composed of cytoplasm, which has electrical resistance. An electrical threshold exists at the axon hillock, which decides whether a signal will be passed to the axon. If the graded potential is larger than the threshold upon reaching the axon hillock, an action potential will occur and the signal will continue to pass down the neuron. If the graded potential is smaller than the threshold, then an action potential will not occur and the signal will be stopped. Now, as the signal travels through the axon, it will attenuate further.

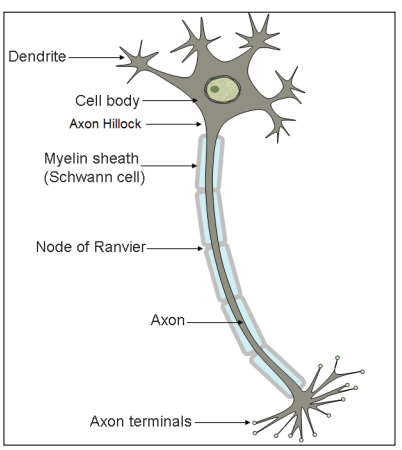

Fig. 1. Adapted rudimentary nerve cell.[6]

At each node of Ranvier including the axon hillock, the signal, assuming it stays above threshold, is reconstructed by a sodium ion channel located at the node, thus boosting the signal voltage up and mitigating the signal degradation. To aid in transmitting this signal, some animals, including humans, produce a fatty tissue called myelin, which insulates the axon from surrounding materials and minimizes signal leakage from the axon. The myelin also contributes to the capacitive properties of the axon and affects the speed that electrical impulses are transmitted through the nerves. In humans, however, certain congenital problems can cause demyelination, allowing the signal to leak out of the axon between the nodes of Ranvier and fall below threshold, resulting in overall loss of the signal. Demyelination is believed to be the underlying cause of the disease multiple sclerosis.

Laboratory experiment

• *Apparatus*

The apparatus consists of two pieces of vinyl tubing approximately 40 cm long, one with inner diameter of 3/16 in and the other 5/16 in. These tubes were then filled with salted gelatin and chilled until the gelatin solidified. I used Knox® gelatin and a recipe of one envelope of gelatin, one cup of water, and one teaspoon of table salt. To make the apparatus more robust for multiple uses, I used, as seen in Fig. 2, two binding-post-to-banana-plugs forced into the ends of the 5/16-in tubing and dual binding post mounts super glued onto the ends of the 3/16-in tubing. This prevents gelatin from coming out the ends of the tubes after each insertion of the wires.

Both sets of adapters must make contact with the gelatin. Resistors will also need to be inserted into the gelatin to

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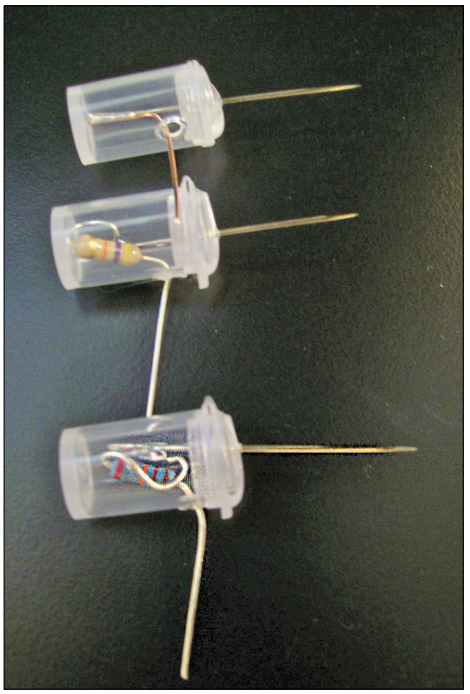

Fig. 3. Negligibly resistive probe (top), 47-kΩ resistive probe (middle), and 12-kΩ resistive probe (bottom).

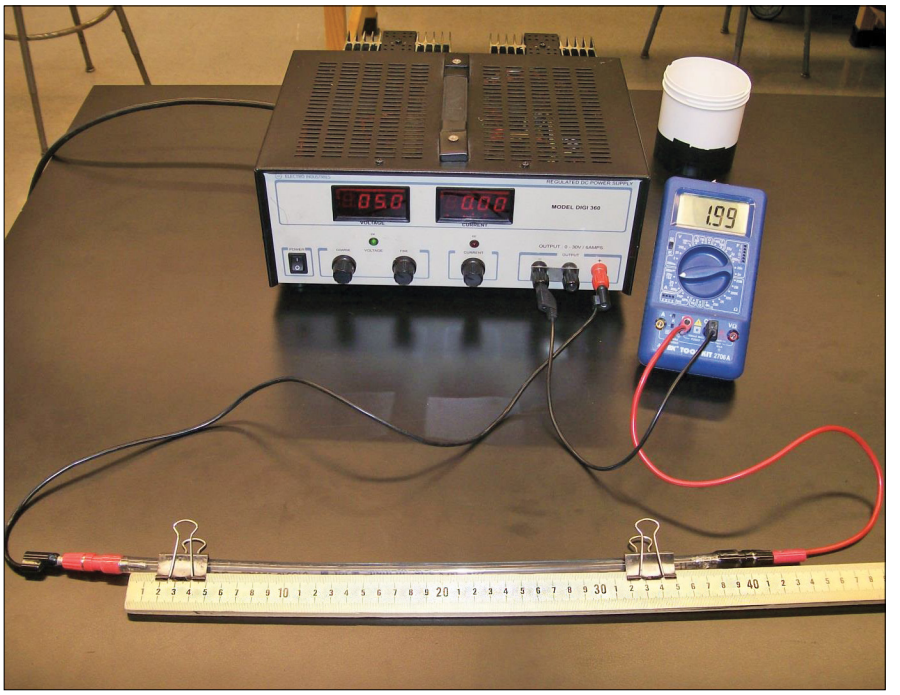

Fig. 4. The setup of a gelatin tube attached to a meterstick with an ammeter and power supply.

correctly model axons. Again, to make the apparatus more robust and prevent the mangling of resistors with each insertion, both resistive and negligibly resistive probes were constructed. The probes were constructed by forcing a needle through the cap of a 0.924-mL polypropylene micro vial with a resistor, or wire as needed, soldered to the needle with the other end protruding out the side of the vial. Figure 3 shows examples of the resistive probes and the negligibly resistive probes.

Physics – Resistance of materials

Axon dimensions (both length and diameter) vary across the animal kingdom and even within the human body, so students should first explore and learn the effect of length and diameter on the resistance of materials. Using the apparatus described above, students can measure the resistance of the gelatin along the length of each tube by piercing the side of the tube with a negligibly resistive probe. Contact resistance between the probes and the gelatin is a concern, so to best execute this procedure, the four-wire method must be employed. For good data, a power supply set between 1.5 and 4 mA and an ammeter should be connected to the ends of the tube, as shown in Fig. 4.

The value of the current must be monitored for fluctuations as the gelatin warms. Using a voltmeter, the voltage between the end of the first wire and the gelatin can be measured along the length of the tube. These data can be analyzed by calculating the resistance using Ohm's law and plotting the resistance versus length. The slope of this plot, along with the cross-sectional area of the gelatin, can then be used to extract the resistivity ρ of the gelatin using the equation:

$$R = \rho \frac{L}{A}. \tag{1}$$

This process is then repeated for the other tube. The gelatin recipe will produce a resistivity of $27 \pm 2\ \Omega\,\text{cm}$.

It should be noted that while some portions of the biology/neuroscience community use resistivity, others use conductivity, σ. The lab can be changed at the reader's discretion to focus on conductivity by using the equation:

$$R = \frac{L}{\sigma A}. \tag{2}$$

Biology – Neurons, axons, and demyelination

These same gelatin tubes can now be used to model axons. Insert a 47-kΩ resistor probe 25 cm down the length of the tube to represent the subsequent neuron or muscle tissue. Connect its other end to the power supply set at 10 V, as shown in Fig. 5. For this experiment, declare 8 V as the threshold of the axon hillock and nodes of Ranvier.

By measuring the voltage between the probe and ground along the length of the tube, as described, students can observe that the measured voltage drops slightly with each consecutive measurement. While this does not quite model the behavior along the total length of the axon correctly, it does model the behavior of the graded potential within the cell body and the behavior between nodes of Ranvier. This process can be repeated with the other tube and it should be noted that the larger tube diameter maintains a higher volt-

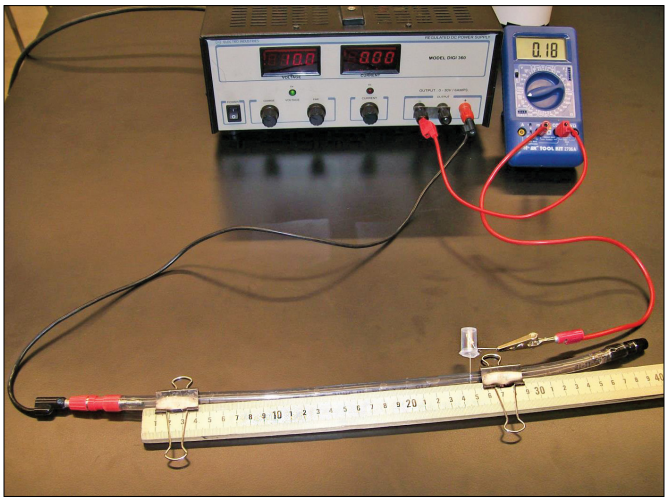

Fig. 5. Axon model with a 47-kΩ resistor probe modeling subsequent tissue.

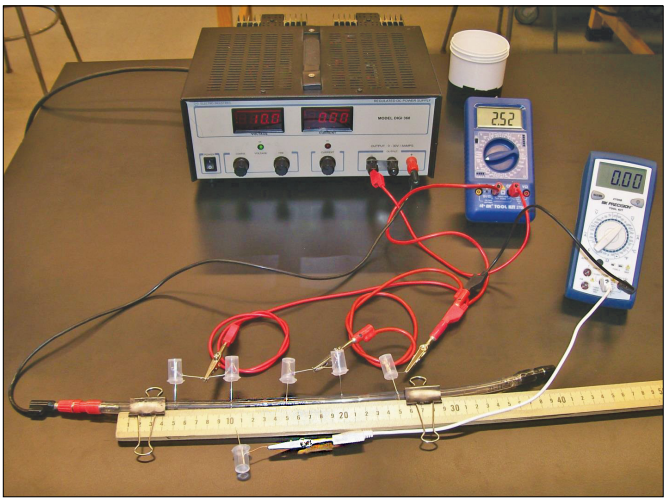

Fig. 6. Multiple 12-kΩ probes are used to model demyelination. The use of the negligibly resistive probe can also be seen.

age. By using Kirchhoff's laws and modeling the cell body as a resistor, the requirement of a graded potential in the cell body can now be illustrated.

Finally, multiple sclerosis and demyelination of the axon can be modeled. This is done, as shown in Fig. 6, by inserting four 12-kΩ resistor probes into the holes made previously at 5-cm increments and connecting the other ends of the resistors to the power supply.

These new resistors will represent "leaky channels" or damage to the surrounding myelin tissue. Measure the voltage at each resistor by piercing the tube a second time at the 5-cm sites with a negligibly resistive probe, but being careful not to connect the probes in the gelatin while taking measurements. A much larger voltage drop now occurs with each measurement, and the eventual failure to maintain threshold for signal replication at a subsequent node of Ranvier also occurs. This process can be repeated with the larger diameter tube, and the observation that the failure to maintain threshold occurs further down the length of the larger diameter tube can be made.

Analysis of these results should be done by relating the physics of circuits and Kirchhoff's laws and the resistance equation. Conclusions should be drawn through the modeling of the biological system as a circuit with sections of axons represented by small resistors, and leaky channels represented by larger resistors.

The laboratory portion of this experiment uses prescribed instructions for students to follow rather than asking students to design an experiment and decide which measurements to take. This approach is primarily used because of the complex material and interdisciplinary nature of the lab. The questions provided in the lab ask students to compare the response to that of both the axon and the cell body. Students are also asked to examine, based on their data, what aspects of the axon could be changed to provide better axon function. These questions probe their understanding of physics and its relationship to the length and diameter of axons. Biology concepts are also reinforced by asking students to draw conclusions about evolution and the differences in axons across the animal kingdom. The measurements are designed for knowledge and comprehension of the material while the questions asked help students solidify the connection between physics and biology, and require students to analyze and synthesize.

It should be noted that the actual process of signal transmission down an axon is different and more complex than the simple conduction of electricity, as suggested here. A good, basic explanation of nerve cells, axons, and particularly action potentials for instructors and interested students can be found at http://hyperphysics.phy-astr.gsu.edu/hbase/biology/actpot.html. This resource highlights where the lab's analogy and the actual process deviate.

Student perception

Students performing this lab have commented positively on its relevance to their field of study. They have claimed to have a better understanding of both the biology of axons and the physics of resistance and circuits after completing the lab. Moreover, student surveys suggest that they particularly appreciated the modeling and analysis of demyelination. Some stated that not only were they able to see the underlying reasons for axon response when functioning properly, but they thought it was interesting to see and understand the consequences of failure of these biological functions. These student surveys were provided with the lab manual to all students and were completely voluntary, with 92 out of 106 students submitting surveys. Some of the questions on the survey asked students to rate whether the lab was clear and understandable, whether the lab helped them learn topics of resistance and resistivity, whether the lab helped them to see the connection to their major discipline, and also left space for additional comments. Completed surveys were collected by lab instructors and kept confidential until the term was over to ensure impartiality. Some students, however, also gave feedback to me personally. While these data are anecdotal,

the author believes that students have a positive response to this experiment, and that it improves learning and understanding of both physics and biology.

Conclusion

This experiment is meant to be one response to the call for better physics education for future physicians and life scientists. It is hoped that this laboratory procedure will inspire and encourage readers to continue to bridge the gap between physics and biology. More physics laboratory experiments should be developed in an attempt to better teach physics through a biology focus and improve students' motivation to learn physics.

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