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*Published in:*
Advances in Physiology Education

*DOI:*
10.1152/advan.00054.2021

*Publication date:*
2021

# Teaching bioelectricity and neurophysiology to medical students using LabAXON simulations

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**Abbreviated title:** LabAXON practical session

**Keywords:** Nernst potential, ion channels, patch-clamp electrophysiology, education

## Abstract

Patch-clamp electrophysiological recordings of neuronal activity requires a large amount of space and equipment. The technique is difficult to master and not conducive for demonstration to more than a few medical students. Therefore, neurophysiological education is mostly limited to classroom based pedagogies such as lectures. However, demonstration of concepts such as changes in membrane potential and ion channel activity is best achieved using hands-on approaches. This article details an *in silico* activity suitable for large groups of medical students, which demonstrates the key concepts in neurophysiology using the LabAXON simulation software. Learning activities in our practical include: 1) measurements of voltage and time parameters of the neuronal action potential and its relationship to the Nernst potentials of $Na^+$ and $K^+$; 2) determination of the stimulus threshold to evoke action potentials; 3) demonstration of the refractory period of an action potential; 4) voltage-clamp experiments to determine the current-voltage relationship of voltage-gated $Na^+$ and $K^+$ channels, the voltage-dependence of, and recovery from, inactivation of voltage-gated $Na^+$ channels. We emphasized the accuracy of quantitative measurements, as well as the correct use of units. The level of difficulty of the activity can be altered through different multiple choice questions relating to material introduced in the associated lectures. This practical activity is suitable for different class sizes and is adaptable for delivery using online platforms. Student feedback showed that the students felt the activity helped them consolidate their understanding of the lecture material.

**Snapshot**

This article details the use of the LabAXON software in teaching basic neurophysiology to undergraduate medical students. Student perceptions about the activity was obtained using anonymous feedback. Our experience showed that LabAXON was easy to implement and students found the activity engaging and helped them consolidate the basic neurophysiology concepts. Some of the weaknesses and wider implications to medical student teaching are discussed.

## Introduction

The generation of an action potential is one of the crucial concepts which underpins basic neurophysiology teaching to medical students. Understanding the action potential and basic neuronal function requires medical students to have a basic grasp of bioelectricity, such as an appreciation of Ohm's Law, the Nernst potential and the maintenance of the resting membrane potential. Demonstration of these concepts to students is largely limited to texts, graphs and mathematical formulae (9). These are usually delivered using pedagogies such as lectures and small group tutorials, and are not conducive for interactive learning. Interactive approaches to learning can enhance a student's understanding, interest and performance in a particular topic (1, 10, 11, 16). Therefore, whilst lectures are the most common way to introduce medical students to basic neurophysiology, consolidation of these concepts may require more interactive approaches.

Demonstration of bioelectricity, action potentials and ion channel function requires patch-clamp electrophysiology. The minimal patch-clamp setup requires a large amount of space and is expensive (14). Furthermore, patch-clamp experiments are labor intensive and requires substantial training. Therefore, using patch-clamp electrophysiology as an interactive teaching tool is not realistic. There are a number of interactive tools for neurophysiology, such as MetaNeuron (12), Neurodynamix II (6), Neurons in Action (21) and LabAXON (15). The LabAXON software in particular is a free Microsoft Windows-based simulation software of the squid giant axon. The simulation itself utilizes the model of the classic squid giant axon experiment from Hodgkin and Huxley in 1952 (8). This model describes the flow of $Na^+$, $K^+$ and leak currents across a cell membrane to produce the characteristic changes in membrane potential which underlies the action potential.

Despite the availability of these interactive tools to demonstrate basic neurophysiology, student feedback on the benefits of these tools are scarce. We therefore implemented a series of *in silico* activities using the LabAXON software with our Year 2 Bachelor of Medicine and Bachelor of Surgery (MBBS) students, and conducted an anonymous feedback survey of the activity. These activities complemented the lecture material, and students could consolidate their knowledge through answering multiple choice questions as they worked through the activities. Students performed virtual experiments using LabAXON, and answered questions which underpinned the following key learning objectives: 1) define the Nernst potential, and describe its relationship with ionic gradients; 2) discuss the dependence of the resting membrane potential on $K^+$; 3) describe the concept of a threshold in action potential generation; 4) measure the refractory period of the action potential; 5) investigate the voltage-dependence of voltage-gated $Na^+$ and $K^+$ ion channels (VGSC and VGKC, respectively) and 6) explore the voltage-dependence of inactivation of VGSC and its recovery. In this article, we share details of our practical, our experiences and also the data from our anonymous student feedback of the practical.

**Methods**

*Setting* – The LabAXON activity was carried out with our second-year MBBS students (n = 42), during their nervous system block, consisting of a series of lectures, team-based learning sessions, practical and clinical skills sessions. Prior to the LabAXON activity, students received lectures covering basic neurophysiology. These included bioelectricity, membrane ion transport, the generation and maintenance of the resting membrane potential, chemical neurotransmission and synaptic integration of electrical signals. The activity was run in a computer laboratory. Each student had access to a Windows 7 computer with LabAXON 5.2 software installed. The Microsoft Windows-based software is available free for academic purposes (at https://www.labheart.org/). The practical was timetabled for 3 hours.

*Activity design* – The design of the activity complemented the material delivered in the lectures, and was based on some of the available activities in the LabAXON Workbook written by Donald Bers and Jose Puglisi from University of California (also available to download at https://www.labheart.org/). Our LabAXON activity booklet can be downloaded as Supplementary Information 1 (https://doi.org/10.6084/m9.figshare.14402354) to assist colleagues in the educational community to implement similar activities. A key to this activity booklet is available upon request. Each student was given a booklet and instructed to complete the exercises, and also answered multiple choice questions during the 3 hour session which linked to key learning objectives covered in the lectures. We also emphasized to our students to provide quantitative information to three significant figures, with the correct units. Students were aware from the beginning of the practical session that their completed practical booklet would be assessed. The activity was divided into 7 parts, and the recommended time to spend in each section was indicated in the booklet: 1) Making simple measurements (15 min), 2) The membrane potential (15 min), 3) The stimulus threshold (30 min), 4) The refractory period (30 min), 5) VGSC and VGKC current-voltage relationship (20 min), 6) VGSC voltage-dependent inactivation (20 min) and 7) VGSC recovery from inactivation (20 min).

Four faculty members and one technician oversaw the activity. All people involved were briefed on the activity and a run through of the activity booklet was performed to ensure that the exercises were achievable and logical. Any issues with the activity booklet were raised and dealt with immediately. The key to the questions were also discussed and all agreed with the answers. Completed booklets were marked according to this key.

*Specific activities* - Parts 1 to 4 utilized the current-clamp mode of the LabAXON simulator to record changes in membrane potentials. *Part 1* involved making simple measurements to allow students to familiarize themselves with the user interface of LabAXON, particularly the use of the cursors. They measured the resting and peak membrane potentials, and calculated the action potential amplitude. They also measured $Na^+$ and $K^+$ peak conductances, as well as the time from the beginning of the stimulus to the peak of the action potential. *Part 2* focused on the resting membrane potential and the effect of increasing extracellular [$K^+$]. We linked concepts such as the Nernst equation and equilibrium potentials in this section. Students were also asked questions related to the threshold and the influence of the membrane potential on VGSC activity. *Part 3* expanded further on the action potential threshold and students measured the stimulus strength to fire an action potential given different pulse widths. They plotted the relationship between pulse width and the stimulus intensity and were asked questions about the *in vivo* correlates of the simulation, in relation to the summation of different excitatory inputs at the dendrites. *Part 4* of the activity looked at the refractory period. Students simulated two consecutive action potentials at a defined interval. They modified this interval and determined the stimulus intensity to evoke an action potential. These were plotted to illustrate the inverse relationship between stimulus intensity and interval between action potentials. Students were asked questions about the absolute refractory period.

Parts 5 to 7 of our LabAXON practical utilized the voltage-clamp mode of the simulator which allowed us to measure the currents flowing through the VGSCs and VGKCs. *Part 5* looked at the basic current-voltage relationship of VGSCs or VGKCs. We encouraged students to think about the shape of the ensemble currents, and how to isolate currents through a specific ion channel to study its function. The students then applied either tetrodotoxin or tetraethylammonium via the LabAXON simulator to isolate VGKC currents or VGSC currents, respectively. We also encouraged students to think about the driving forces for ion movement, and its influence on the magnitude and direction of current flow. *Part 6* looked at the inactivation of the VGSC, and how it is influenced by membrane potential. Students were encouraged to make sense of the voltage-dependence of inactivation curve, as well as the voltage-command protocol which produced the data. The influence of drugs which target the VGSC (e.g. local anaesthetics) were explored. Local anaesthetics (such as lidocaine) are known to stabilize the inactivated state of the VGSC and shift the voltage-dependence of inactivation curve to the left (2, 5). *Part 7* of the practical allowed the students to explore the recovery of VGSCs from inactivation, using paired-stimulation protocols of increasing intervals.

*Activity assessment* – Students were asked to submit their activity booklets at the end of the session. These were marked by faculty members according to the pre-agreed key. Numerical answers were given a 10% error margin. However, numerical answers not expressed in three significant figures or had wrong units were marked wrong. The marked booklets were re-distributed to the students and the answers were discussed.

*Student feedback survey* – Towards the end of the practical session, students were encouraged to complete an anonymous feedback on the activity. We emphasized to the students that completion of this feedback was anonymous and voluntary. The feedback consisted of 13 questions and was delivered via Google Forms using a QR code given to the students. The complete questionnaire is given in Supplementary Information 2 (https://doi.org/10.6084/m9.figshare.14402354). All questions were in a multiple choice format. The main purpose of taking the feedback was to obtain student perceptions about the use of the activity in achieving the learning objectives. We also explored which aspect of bioelectricity and neuroelectrophysiology students found most challenging. Finally, we also gauged whether taking part in these interactive simulation experiments may have stimulated students' interest in learning more or getting involved in neuroscience research. The final question of the feedback asked for student consent to use their responses for potential publication. Approval was also obtained from the institutional Ethical Review Committee of Macau University of Science and Technology to publish the anonymous student feedback data.

*Data analysis* – Student scores from the activity were converted into percentages and sorted into 5% bins. The counts in each bin were plotted as a distribution histogram. Responses from the survey were expressed as raw counts and percentages.

## Results

*Practical aspects of running the activity*

At the time of publication, the MBBS program at the Macau University of Science and Technology is the first and only MBBS program in the city (13). The first cohort of students were admitted in 2019. The first two years were the pre-clinical years, during which students attended a foundation block, followed by 9 systems blocks. Our LabAXON activity was run with our first cohort of students during nervous system block in the second semester of Year 2. Prior to the activity, students had lectures covering basic neurophysiology concepts. Students were asked to revise these materials before the activity.

The LabAXON activity began with a short introduction to the software, some of the key features of the interface and instructions on completing the activity booklet (Supp. Info. 1; https://doi.org/10.6084/m9.figshare.14402354). Students were asked to provide quantitative values to three significant figures with appropriate units.

Students then worked their way through the booklet. Any student queries were dealt with by faculty members immediately. The most common queries related to the toggling and use of the cursor function to measure current or voltage values. Other questions related to navigating the sub-menus of LabAXON to toggle between the various stimulation modes (e.g. paired pulse or current/ voltage-clamp), the setup of the axes to plot duration-intensity graphs and the definition of significant figures. Students also often neglected to reset the software parameters (by clicking the default button) before performing a new experiment.

The activity booklet included the recommended amount of time students should spend in each section. The first student completed the activity after approximately 2 hours, with a few requiring the full 3 hours to complete the activity. All students completed the activity within 3 hours. As students completed the activity, they were reminded to complete the feedback form. We emphasized to the students that the feedback was anonymous and voluntary.

All booklets were collected and faculty members involved marked the booklets according to the key. The distribution of students' scores is shown in Figure 1. The median score was 92% with a S.D. of 6.23 (n = 42). The distribution of scores was approximately bell-shaped, with the exception of one score of 63%. This particularly low score was a result of numerous mistakes with significant figures.

*Student feedback on LabAXON activity*

We asked students to fill out a feedback form after they had completed the activities (Supp. Info. 2; https://doi.org/10.6084/m9.figshare.14402354). Out of 42 students present, we received 41 responses. Four students did not give consent for their survey results to be published and therefore these were removed from the analysis. Therefore, a total of 37 responses were included in the analysis.

Students were asked about the practical aspects of the activity, i.e. whether the activity booklet was easy to follow, whether they needed guidance from teachers, and whether they felt the teachers had sufficient knowledge of the subject matter and the activity. These data are summarized in Table 1. 81% of responses agreed (20 students) or strongly agreed (10 students) that the activity booklet was easy to follow. 70% of responses agreed (16 students) or strongly agreed (10 students) that they needed guidance from teachers. Students also thought that the teachers had sufficient knowledge of the subject and the activity, with 92% and 86% respectively agreed or strongly agreed. No students disagreed or strongly disagreed that the teachers had sufficient knowledge of the subject or activity. Our data therefore suggests that the prior preparation of the activity involving faculty members was an important component.

We provided a suggested time to complete each section of the activity in the booklet. We asked the students whether they were able to finish the activity within the allocated time. 34 students (corresponding to 92% of the responses) responded “Yes”, indicating that the suggested time provided in the booklet was appropriate.

Ahead of the activity, we asked the students to revise the relevant lecture material. 28 students (corresponding to 76% of the responses) responded that they heeded our advice. We also asked the students about their knowledge regarding bioelectricity and neuronal excitability before the activity. The majority of responses were average (68%, 25 students). 29% of responses were novice (2 students) or below average (9 students). 1 student responded that their knowledge was expert. The vast majority of responses referred to the difficulty level of the activity as appropriate (76%, 28 students), with 24% responding the activity was too difficult (9 students). No student responded that the activity was too easy. We also explored which of the concepts the students found the most challenging. For this question, students were allowed to select as many choices as they wished. The results are shown in Figure 2. 84% of responses (31 students) included VGSC inactivation as the most challenging topic. This was followed by the refractory period (59%, 22 students), membrane potential changes as a result of ion channel activity (35%, 13 students), Ohm’s Law (24%, 9 students), reversal potentials (24%, 9 students) and the all-or-none principle of the action potential (14%, 5 students).

The main objective of the activity was to help students consolidate their knowledge on basic bioelectricity and neuronal excitability. We therefore asked our students whether the activity had achieved this objective. Student responses are summarized in Table 2. 65% of responses agreed (23 students) or strongly agreed (1 student) that the activity had consolidated and enhanced their knowledge. 27% (10 students) had a neutral response. 8% of responses disagreed (1 student) or strongly disagreed (2 students) that the activity had an impact on their knowledge. We also asked the students if they found the activity enjoyable and engaging. 70% of responses agreed (21 students) or strongly agreed (5 students). 19% (7 students) responded neutral and 11% disagreed (3 students) or strongly disagreed (1 student). Overall, the data indicate that the activity had achieved its objective and that our students found the activity enjoyable and engaging.

We also asked our students whether they would like to learn more about electrophysiology related research. 51% of responses agreed (18 students) or strongly agreed (1 student). 41% of responses (15 students) had a neutral response and 8% disagreed (3 students). By contrast, students' responses to whether they would like to get involved with ion channel/ neuroscience research were less enthusiastic, with 25% agreed (8 students) or strongly agreed (1 student) that they would like to be involved. 65% of the students gave a neutral response (24 students) and 10% disagreed or strongly disagreed (5 students in each category) that they want to get involved in neuroscience research.

**Discussion**

There are several simulation software available for basic neurophysiology. Some of these have already been used in undergraduate teaching. MetaNeuron simulates neuronal behavior (12). It is used in a number of institutions but feedback data are scarce. Student feedback on MetaNeuron from the University of Minnesota Medical School suggests that the software is useful as a learning tool (12). Neurons In Action is a series of 25 hyperlinked tutorials and interactive simulations of patch-clamp experiments (21). No formal feedback of its practical use is available. Neurodynamix II uses electrical circuits to help students build the conductance model from Hodgkin and Huxley (6). Its use in a semester long undergraduate teaching program showed a gradual improvement in student knowledge (4). These studies showed that the use of interactive simulations for neuronal function can help students gain valuable insight and consolidate their classroom based knowledge. In designing the first nervous system block for our newly established MBBS program, we implemented the LabAXON software (15) in an interactive activity with our second-year students. We found the LabAXON interface to be very user-friendly, simple to implement and also allowed for a great deal of flexibility on the topics and concepts to explore with our students. Student feedback of our LabAXON activity is the first formal analysis of its use in undergraduate MBBS teaching. Our data showed that students mostly agreed that our LabAXON activity has enhanced and consolidated their knowledge regarding basic neurophysiology. However, our conclusions are limited to students' perceptions of learning and knowledge. It would be helpful to correlate the assessment scores with the responses in the student feedback survey, to gauge actual learning and knowledge. Nevertheless, it is arguably more important that such feedback was collected in an anonymous manner, in order to obtain honest responses from the students. Indeed, we emphasized to the students that completion of the feedback was anonymous and voluntary. This precluded any correlation analyses and represented a weakness in our analysis of the activity.

Furthermore, it is also possible that any additional sessions will offer additional chances for students to consolidate their knowledge. The activity was run with our first cohort of MBBS students and as a result we lack a true control group, for example a past cohort of students. In depth analyses of these interactive teaching tools in the future will benefit from a control group. Furthermore, survey questions which allow students to select the most appropriate response, as opposed to agreement with leading statements, may also offer further insight into the use of LabAXON as an interactive teaching tool.

Our experience with LabAXON showed that one of the key components was the activity booklet. Student feedback of the booklet was overwhelmingly positive. It is our opinion that the effort and time put into discussing the details of the booklet, and also doing a "dry-run" of the activity was critical to its implementation. It also helped teachers involved to go through the answers which simplified the assessment of the activity.

Our data indicated that most students scored very well in the activity, with a median score of 92%. The range of scores had a lower range of around 80%, with one outlier of 62%. This outlier score was due to numerous mistakes in returning the correct number of significant figures required. Nevertheless, the scores suggest that the exercises within the activity might be too easy. This was not reflected in the student feedback. The vast majority of students thought that the difficulty level of the activity was appropriate, with around a quarter saying it was too difficult. Our student feedback also indicated that VGSC inactivation and the refractory period were among the more challenging concepts. Other colleagues interested in implementing this activity at their institutions can expand on the topics which students found challenging. The activity was not conducted under strict examination conditions, and students were encouraged to discuss their work with peers and teachers. Students may also have conferred their answers with their peers, which may have led to more homogenous scores. The content and difficulty of the activity can be altered to correspond with the concepts taught in the associated lectures. For example, different multiple choice questions can be asked or short answer questions can be used to test students' understanding of a particular concept.

We used LabAXON as an interactive teaching tool for our second-year MBBS students. The main objective of our activity was to consolidate the main basic neurophysiology topics discussed in the lectures, such as equilibrium potentials, resting membrane potentials, refractory periods and voltage-dependencies of voltage-gated ion channels. These are important concepts for medical students to grasp as some of these underpin the mechanisms of some drugs. For example, local anaesthetics such as lidocaine work through voltage-dependent block, and stabilization of the inactive state of voltage-gated $Na^+$ channels (5). As a result, they are not cardiotoxic due to the very hyperpolarized resting membrane potential of the cardiomyocyte. Understanding the mechanism of action of lidocaine requires a solid grasp of all of the concepts we covered in the LabAXON activity. There are also additional exercises that we have not implemented with our version of LabAXON activity. For example, students can explore single ion channel recordings and relate these to whole-cell currents. This can explore concepts such as ion channel open probability, open time and shut time, and its relationship to the ensemble current. We believe that these advanced ion channel biophysics are not suitable for second-year MBBS students. However, the clinician scientist has an important role to play in modern medicine (23). Their clinical expertise allows them to be uniquely poised to raise specific, focused and translational research questions (18). Nevertheless, the number of clinician scientists has been in decline (18, 20). We therefore believe that basic neurophysiology, biophysics, and also the laboratory techniques which generate these data should be introduced early to medical students, to stimulate their interest towards medical/ academic research in the future, should they wish to pursue such a path. Indeed, our data showed that these interactive activities could motivate students to learn more about and be involved in neuroscience research. It suggests that in a subset of students who might be interested in a clinician scientist pathway, early introduction of interactive activities for traditionally lecture based topics can have an impact on their future career choices.

The LabAXON software, whilst easy to use and implement in interactive teaching sessions, has not been updated since 2009. We installed the LabAXON software on machines running Windows 7 without any problems. However, support and updates for Windows 7 has stopped since early 2020, raising potential compatibility issues with newer operating systems. We have installed and used all of the functions detailed in this activity on machines running Windows 8 and Windows 10 operating systems successfully. Therefore, institutions which use these newer operating systems will also be able to implement LabAXON. Our activity can also be implemented for online, remote delivery. The Coronavirus disease 2019 (COVID-19) pandemic has led to a lot of medical schools conducting some form of online teaching (7, 17, 19, 22). Our faculty had adapted our spirometry practical session to be delivered via Zoom (3). The LabAXON activity described in this article can also be fully implemented for remote delivery. The simplest implementation would be to ask the students to complete the activity booklet offline. More interactive implementations could include the use of conferencing software (e.g. Zoom), share screen and also break-out rooms to allow for small group discussions of the material.

## References

1. **ArmbrusterP**, **PatelM**, **JohnsonE**, **WeissM**.Active learning and student-centered pedagogy improve student attitudes and performance in introductory biology. *CBE Life Sci Educ* 8: 203–213, 2009. doi: 10.1187/cbe.09-03-0025.

2. **Baptista-HonDT**, **RobertsonFM**, **RobertsonGB**, **OwenSJ**, **RogersGW**, **LydonEL**, **LeeNH**, **HalesTG**.Potent inhibition by ropivacaine of metastatic colon cancer SW620 cell invasion and Na V 1.5 channel function. *Br J Anaesth* 113: i39–i48, 2014. doi: 10.1093/bja/aeu104.

3. **BhaskarA**, **NgAKM**, **PatilNG**, **FokM**.Zooming past the coronavirus lockdown: online spirometry practical demonstration with student involvement in analysis by remote control. *Adv Physiol Educ* 44: 516–519, 2020. doi: 10.1152/advan.00097.2020.

4. **CrispKM**.A structured-inquiry approach to teaching neurophysiology using computer simulation. [Online]. *J Undergrad Neurosci Educ* 11: A132-8, 2012. http://www.ncbi.nlm.nih.gov/pubmed/23494064 [1 Apr.2021].

5. **ElajnafT**, **Baptista-HonDT**, **HalesTG**.Potent inactivation-dependent inhibition of adult and neonatal NaV1.5 channels by lidocaine and levobupivacaine. *Anesth Analg* 127: 650–660, 2018. doi: 10.1213/ANE.0000000000003597.

6. **FriesenWO**, **FriesenJA**.*Neurodynamix II: concepts in neurophysiology illustrated by computer simulations.* New York, NY: Ocford University Press, 2010.

7. **HilburgR**, **PatelN**, **AmbrusoS**, **BiewaldMA**, **FaroukSS**.Medical Education During the Coronavirus Disease-2019 Pandemic: Learning From a Distance. *Adv. Chronic Kidney Dis.* 27 W.B. Saunders: 412–417, 2020.

8. **HodgkinAL**, **HuxleyAF**.A quantitative description of membrane current and its application

to conduction and excitation in nerve. *J Physiol* 117: 500–544, 1952. doi: 10.1113/jphysiol.1952.sp004764.

9. **MichaelJ**.What makes physiology hard for students to learn? Results of a faculty survey. *Am J Physiol - Adv Physiol Educ* 31: 34–40, 2007. doi: 10.1152/advan.00057.2006.

10. **MontrezorLH**.Performance in physiology evaluation: Possible improvement by active learning strategies. *Adv Physiol Educ* 40: 454–457, 2016. doi: 10.1152/advan.00022.2016.

11. **MontrezorLH**.Lectures and collaborative working improves the performance of medical students. *Adv Physiol Educ* 45: 18–23, 2021. doi: 10.1152/advan.00121.2020.

12. **NewmanMH**, **NewmanEA**.MetaNeuron: A free neuron simulation program for teaching cellular neurophysiology [Online]. *J Undergrad Neurosci Educ* 12: 11–17, 2013. www.funjournal.org [1 Apr.2021].

13. **PatilNG**, **Baptista-HonDT**, **LamCWK**.A Dream Come True [Online]. 2021. https://www.must.edu.mo/images/FMD/files/FMD_monograph.pdf.

14. **Penner R.**A Practical Guide to Patch Clamping. In: *Single-Channel Recording*. 1995, p. 3–30.

15. **PuglisiJL**, **BersDM**.Teaching Basic Electrophysiology with the Aid of a Computer Program. In: *Annual Meeting of the Biophysical Society*. 2010, p. 409a.

16. **ReinhardtCH**, **RosenEN**.How much structuring is beneficial with regard to examination scores? A prospective study of three forms of active learning. *Adv Physiol Educ* 36: 207–212, 2012. doi: 10.1152/advan.00108.2011.

17. **RoseS**.Medical Student Education in the Time of COVID-19. *JAMA - J Am Med Assoc* 323:

2131–2132, 2020. doi: 10.1001/jama.2020.5227.

18. **RosenbergLE**.The physician-scientist: An essential - And fragile - Link in the medical research chain. *J. Clin. Invest.* 103 The American Society for Clinical Investigation: 1621–1626, 1999.

19. **SahiPK**, **MishraD**, **SinghT**.Medical Education Amid the COVID-19 Pandemic. *Indian Pediatr* 57: 652–657, 2020.

20. **SomekhI**, **SomekhE**, **Pettoello-MantovaniM**, **SomechR**.The Clinician Scientist, a Distinct and Disappearing Entity. *J. Pediatr.* 212 Mosby Inc.: 252-253.e2, 2019.

21. **StuartAE**.Teaching Neurophysiology to Undergraduates using Neurons in Action. [Online]. *J Undergrad Neurosci Educ* 8: A32-6, 2009. http://www.ncbi.nlm.nih.gov/pubmed/23493486 [1 Apr.2021].

22. **WayneDB**, **GreenM**, **NeilsonEG**.Medical education in the time of COVID-19. *Sci. Adv.* 6 American Association for the Advancement of Science: eabc7110, 2020.

23. **ZemloTR**, **GarrisonHH**, **PartridgeNC**, **LeyTJ**.The Physician-Scientist: Career Issues and Challenges at the Year 2000. *FASEB J* 14: 221–230, 2000. doi: 10.1096/fasebj.14.2.221.

**Figure legends**

Figure 1. Frequency distribution of student scores from LabAXON activity. Student scores were binned at 5% intervals. The bin upper limit is shown on the x-axis.

Figure 2. Student responses on topics in neurophysiology they found most challenging. Students were given six choices of basic neurophysiology topics and asked to select those they found challenging. They were allowed to select more than one topic. The number of counts for each topic are graphed. Students found VGSC inactivation and the refractory period the most challenging. The all-or-none principle of the action potential had the least votes, indicating that most students found this topic manageable.