



Teaching Tips (COVID)

Adapting a Human Physiology Teaching Laboratory to the At-Home Education Setting

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Abstract—Teaching labs at the undergraduate level poses unique challenges to a school system forced online by COVID-19. We adapted physiology laboratories typically taught in-person to an online-only format, allowing students to measure personal health data alone. Students used available technology and low-cost devices for measuring respiratory and cardiovascular parameters and analyzed the data for differences in testing conditions such as posture and exertion. Students did not physically interact, which encouraged self-directed learning but disallowed peer-to-peer education. Pre-recorded data was utilized for ECG measurements, which streamlined the process but precluded the interactive act of experimentation. The use of low-cost devices empowered and encouraged students to take ownership of their health and form important connections between their own lives and theoretical physiology. Facilitating communication and TA preparedness is key to smoothly running the virtual lab. It will be important for future virtual labs to be designed to facilitate student interaction, include hands-on experimentation, and encourage personal investigation.

Keywords—Physiology, Education, Laboratories, Virtual learning, COVID-19, Distance education, At-home education.

CHALLENGE STATEMENT

The Biomedical Engineering (BME) program at the University of Southern California (USC) includes a course (BME 403) intended to educate students about physiological systems, specifically the respiratory and cardiovascular system. The lecture portion focused on mathematical methods of utilizing and estimating

variables such as alveolar pressure, anatomical dead space, respiratory ventilator flow rates, blood pressure (according to Bernoulli's equation), and pacemaker parameters. The course also includes a lab session during which students gain hands-on experience with collecting physiological data with commercial and lab tools, which was the main concern of the primary author (Teaching Assistant, TA) and is the primary focus of this article.

The COVID-19 pandemic forced USC to shift the Fall 2020 semester to an online-only format. General science courses at the university employed virtual tools such as Labster to attempt to emulate the lab experience in a fully online setting. However, it is well-documented that although online-only experiences have unique benefits, hands-on learning activities greatly increases students' educational experience, including retention and attitudes towards discovery and engineering.^{2,3,8,12} We believe that hands-on learning is critical for good biomedical engineering education. Therefore, the BME 403 labs were adapted to permit students to perform these experiments from home at a low cost.

NOVEL INITIATIVE

In a typical in-person setting, students would gather once per week for 1.5 h in an educational lab space, equipped with audio-visual equipment, experimental and clinical medical devices, and benches for groups of students to work collaboratively. The TA would give a presentation discussing background information and knowledge of the week's lab, then the rest of the time

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would be used for students to execute the lab. If required, students were able to reenter the lab during TA office hours to complete experiments. Students are required to take notes and analyze data, culminating in two formal lab reports to mark the end of the (1) respiratory section and (2) the cardiovascular section. Students worked in groups of 2–4, but each student was required to produce their own data and reports.

The Fall 2020 labs had a typical number of students (30). Students were provided with a list of low-cost medical devices to acquire during the first week of the semester, totaling less than \$30 USD. A table of the recommended device manufacturers and models is provided (Table 2), but TA-approved alternatives were acceptable. These devices were easily purchasable through online retailers such as Amazon. A low-cost custom textbook was required for the lecture portion of the class, but the lab session did not require use of the textbook and therefore will not be considered in this article. Lab meetings were held over Zoom video conferencing software, with the TA beginning the meeting with a short presentation on the background and clinical relevance of the week's experiments, reflecting the in-person labs. However, the presentation also included a detailed walkthrough of the experiment, including a live video demonstration, allowing students to observe the methodology and ask clarifying questions. To maintain equity for students in different time zones and environments unconducive to education, attendance was not mandatory and sessions were recorded for students to review at any time. Lab reports were still required for the respiratory and cardiovascular sections of the course, but students could "catch up" on lab work at any time before the report due date. Students worked individually.

Respiratory Section

In the traditional format, students typically gathered spirometry data with a clinical spirometer used for validating respiratory disease. They measured forced expiratory volume (1 s), temperature, and forced vital capacity. Data was collected using Vernier software on the lab computers and analyzed to elucidate variation due to posture differences (sitting and standing). The measurements were then repeated using a piezoresistive belt wrapped around the students' chest, which they had to first calibrate. The results of the two instruments were then compared and conclusions were drawn (Tables 1, 2).

In the virtual format, students purchased a Vernier 5000 incentive spirometer (or equivalent) to measure their inspiratory capacity (IC). They were given instructions to maximally inspire through the spirom-

eter after a relaxed exhale to measure IC in both a sitting posture and a supine posture. To provide a greater degree of accuracy, students taped a mm-scale ruler to their spirometers and assume linear scaling between the 500 mL-demarcations on the spirometers (Fig. 1a). Students received lessons on statistical analyses and compared their sitting and supine measurements with the *t*-test statistical method.

Maximum expiratory pressure was measured with a sphygmomanometer removed from a SantaMedical blood pressure cuff (or equivalent, Fig. 1b), which was used in the second set of lab experiments. Students inspired different amounts of air through the spirometer and forcefully exhaled into a short section of tube connected to the sphygmomanometer (included with the blood pressure cuff) to facilitate data readout while exhaling. Students were instructed to ensure a *stable* 1-second reading on the sphygmomanometer before recording data.

Lung Inflation Reflex was monitored using the spirometer and the "Heart Rate Monitor" app (or equivalent) on their personal smartphones. Students were instructed to breath at 0.5, 1.0, and 1.5 L tidal volumes for a few minutes each and record their heart rates at each inhalation volume.

Cardiovascular Section

The in-person lab format had students measure blood pressure, heart rate, and ECG traces with Vernier blood pressure cuffs and integrated pressure sensors, ECG leads and amplifiers, and wireless heart rate monitors. The virtual labs used manual blood pressure cuffs, provided ECG traces for students to analyze, and utilized students' personal smartphones for measuring heart rate (Fig. 1c).

During lab sessions, students were taught to use a Santamedical adult sphygmomanometer to take blood pressure measurements. A supplemental YouTube video was provided for extra clarity.¹⁰ Outside of scheduled lab sessions, students were asked to take their blood pressure over the course of three days: four systolic and four diastolic readings per day—in the morning and evening, and with their arms extended parallel to the floor and perpendicular to the floor. They then were tasked with statistical analysis with the *t*-test method and applying and confirming Bernoulli's equation for blood pressure.

Instead of measuring their own ECG, students were provided ECG traces and asked to analyze them with Einthoven triangle equations discussed in lecture. Further, they had to do external research to determine if the calculated values fell within a range of "healthy" values, or if the traces showed evidence of a heart condition.

TABLE 1. Comparing the traditional in-person lab session with the virtual course

	In-person	Virtual	Specific learning goal
Respiratory experiments	Force vital capacity Forced expiratory volume (1 min) Temperature dependency	Inspiration capacity Lung strength Lung inflation-heart rate reflex	– Understand the effect of personal health history on respiratory function, including respiratory diseases such as COVID-19 – Identify similarities and differences between at-home and clinical devices
Cardiovascular experiments	Automatic blood pressure measurement ECG trace collection ECG analysis Heart rate recovery time	Manual blood pressure measurement ECG analysis Heart rate recovery time	– Understand the theory of non-invasive blood pressure measurement and its comparability to catheter-based measurements – Model physiological data – Process data to demonstrate non-invasive collection of critical health parameters – Explain results with personal health history
Respiratory equipment required	Vernier spirometer 3 L syringe Thermistor Piezoresistive belt Instrumental amplifier circuit Vernier LabQuest	Incentive spirometer Sphygmomanometer Heart rate monitor (Smartphone)	
Cardiovascular equipment required	Vernier digital blood pressure cuff ECG electrodes Vernier ECG amplifier Hand-held heart rate monitors Vernier LabQuest	Blood pressure cuff Sphygmomanometer Heart rate monitor (Smartphone)	
Group sizes	2-4 students per group	Individual	
Report submissions	Individual	Individual	

TABLE 2. Specific materials required for virtual lab

Equipment	Model ^a	Cost	Link
Incentive Spirometer	Voldyne 5000 volumetric Exerciser	\$6.89	https://www.amazon.com/gp/product/B000PAR7KQ/
Blood Pressure Cuff + Sphygmomanometer	Santamedical Adult Deluxe Aneroid Sphygmomanometer	\$22.95	https://www.amazon.com/gp/product/B00ACBKNS6/
Heart Rate Monitor	Android: Heart Rate Monitor iOS: Instant Heart Rate: HR Monitor	Free	Android: https://play.google.com/store/apps/detail?id=com.repsi.heartrate iOS: https://apps.apple.com/us/app/instant-heart-rate-hr-monitor/id409625068
MATLAB with Curve Fitting Toolbox	MATLAB R2020b	Free	Provided by the University

^aWhile these models and apps are recommended, similar TA-approved equipment and apps were permitted in cases where acquiring recommended materials was difficult.

Finally, students were provided a beat-to-beat heart rate chart depicting an “off” transient. They were guided to quantize and digitize the data and fit it to a second-degree exponential function within MATLAB with specific coefficient parameters to generate a mathematical model that accounted for the fast and slow responses of the sympathetic and parasympathetic nerves. Students also performed the YWCA step test (a short YouTube video was used to demonstrate

the process) using a digital metronome and any elevated step they could find at their home.¹¹ While performing the exercise, they used their smartphones to measure their heart rates at each minute mark for 3 min, then continued to measure their heart rate after stopping the exercise. They timed and reported their heart rate recovery time.

All smartphones with cameras are capable of measuring heart rate, since apps utilize photoplethysmog-

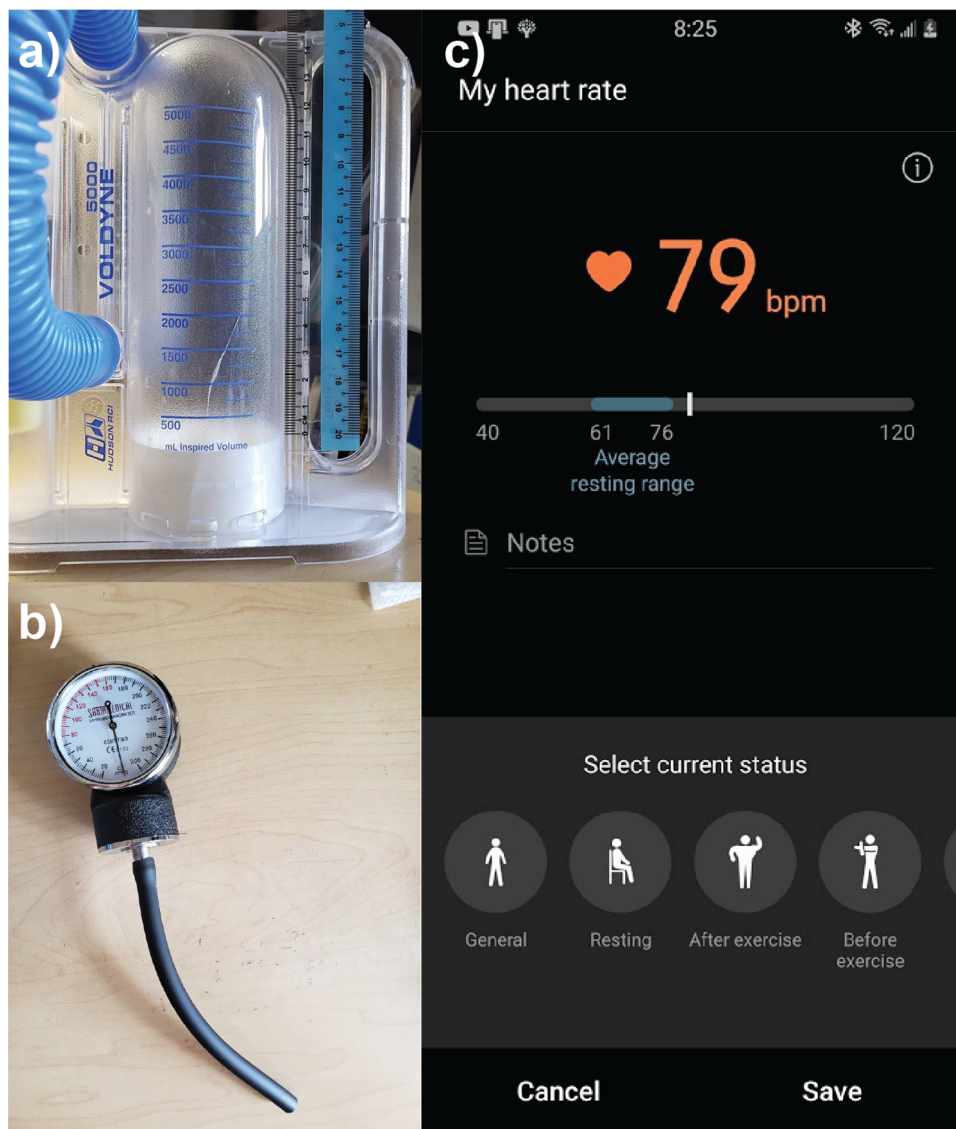


FIGURE 1. A few of the modified tools used for the virtual lab, including (a) a mm-scale attached to an incentive spirometer, (b) the sphygmomanometer from a manual blood pressure cuff (not pictured, but also used separately), and (c) smartphone apps for measuring heartrate (pictured: Samsung Health).

raphy algorithms with their back cameras. These apps have been shown to accurate enough to detect atrial fibrillation.⁹

REFLECTION

On the Lack of Physical Interaction

One of the most significant drawbacks of the virtual physiology lab is that students were unable to physically work together. To a great extent, in-person labs are valuable for their collaborative format, where discussion is natural and encouraged—this increases learning and retention.^{1,13} While not very difficult to execute, the experiments can be challenging to under-

stand. During the in-person format, weaker students typically sought assistance from stronger students during data collection and processing. Stronger students had a chance to sharpen their skills and knowledge by discussing and guiding weaker students. This collaboration was not facilitated or encouraged by a virtual environment, and while some students have worked together in thinking through their data, the majority of students worked alone or sought help from the TA.

It is worth considering methods to bring together the best of both situations. One possibility is to have students work together in pairs. This would facilitate learning through communication and discussion, while the distance imposed by the virtual education format

would still require each student to work independently. Another way to encourage collaboration is to offer extra credit for reaching out to their peers and testing subject-to-subject variance.

On the Use of Pre-recorded Data

In an in-person lab session, students would typically spend much of their time attempting to collect ECG data from themselves and their partners. In the virtual setting, students were provided with prerecorded data that they needed to interpret. While the hands-on learning experience is lost, this saves a great deal of time. Collecting clean ECG traces is often difficult and time-consuming for untrained and inexperienced students, and TAs would then have to individually verify the traces before analysis could be performed. This created time pressure and added frustration to the typical levels of confusion students experienced when constructing and using the Einthoven triangle and related equations to interpret data. Giving students the same prerecorded ECG data to analyze (i) streamlined the experiment, (ii) allowed independent work, and (iii) standardized reported results. The standardization not only made grading simpler, but also enabled students to compare their findings more easily with their peers and investigate anomalies and differences without requiring TA input. We would be remiss to downplay the importance of physical troubleshooting, and a hands-on ECG experiment should always be preferred, since it provides important experience with the technique. But in a virtual environment where efficiency is important and TA assistance is at a premium, providing these complex datasets allows students to understand the key ideas of ECG and learn how to process and interpret the data.

On the Use of Generic, Low-Cost Equipment

Requiring students to obtain their own equipment to perform the experiments had a few drawbacks. Some students, particularly those with international shipping addresses, were significantly delayed in receiving their equipment, and some did not receive their equipment at all. In the case of international students, when suitable alternatives could not be acquired in time, select students were permitted to share data with them provided that data analysis and report writing was performed independently. This preserved students' ability to learn data processing and interpretation.

In the future, USC could charge a "lab fee" and mail equipment to students ahead of time. This has previously been done in USC's electrical engineering department and would streamline course administra-

tion and further standardize equipment. In-person lab formats typically included the cost of materials in a university "lab fee" charged to the student's account, often in the range of hundreds of dollars. In the virtual format, the biomedical engineering department eliminated this lab fee. Thus, we considered the cost of the equipment (< \$30 total) to be affordable for students, especially in the context of other costs associated with attending USC, such as textbooks.¹⁵ If these relatively low costs continue to pose barriers for student education, we imagine that small department-level scholarships could remove these barriers for students, especially if the fee is charged to students' account.

The use of smartphones for heart rate monitoring did not pose an issue. All students had access to a smartphone with a camera and the free apps required. We do not foresee smartphones to be a significant barrier to these experiments due to their vast ubiquity. In rare cases where smartphones are inaccessible, a low-cost finger pulse oximeter could be provided by the university.

Measurement accuracy is decreased compared to shared clinical equipment. Therefore, experiments were modified to accommodate the more inaccurate nature of the equipment. For example, instead of testing for forced expiratory volume, which would require a flow meter-equipped spirometer, lung strength was tested instead. Additionally, *t*-test statistical analysis was used not only to confirm statistical differences between the two postures for IC measurements, but they were also used to verify that statistical differences did *not* exist between tests within the same treatment groups. In data analysis, the TA emphasized identifying correlations and patterns over exact calculations. By adapting the curriculum to available resources and focusing on learning technique and theory, we did not need to draw comparisons between gold-standard equipment and at-home methods.

We also found that many in-person lab techniques and practices could be adapted for at-home experimentation and can expand the scope of learning. For example, the YMCA Step Test is an easy, standardized way for students to increase their heart rate, requiring nothing more than a metronome, stair, and smartphone to measure heart rate (Fig. 1c). Variability in inspiration capacity could be compared between standing and supine postures, the latter enabled by the students' beds. This measurement is particularly relevant during the COVID-19 pandemic, since the disease affects lung volume and gas exchange.^{4,14} At-home measurements also allowed students to take measurements over time, instead of just single-day measurements. To take advantage of this, students were asked to take their blood pressure over a series of days, keeping the time of day relatively consistent. This

approach to data collection is more realistic and led to better discussions around statistical analysis.

Another positive outcome of this approach is that students took greater ownership of their work. Students learned that physiological data can be measured with low-tech devices such as incentive spirometers, blood pressure cuffs, and sphygmomanometers. They were taught that important physiological parameters can be easily measured, and that medical device development often improves on basic devices' accessibility, reliability, and accuracy. Basic theory and principles of certain physiological measurements was emphasized. For example, while in-person lab sessions typically have students use blood pressure cuffs with integrated sensors, the virtual labs taught students how to take a blood pressure manually, drawing logical connections between systolic and diastolic pressures, air cuff pressure, and sphygmomanometer readings.

Students also began including their own interpretations of their data in relation to their personal health history. When they collected data that fell outside of nominal "healthy" values, students often offered up past respiratory conditions (i.e. asthma) and decreased physical activity due to the COVID-19 pandemic as explanations. It was encouraging to see students make connections between theoretical knowledge and real-world conditions. It is important for the lab facilitator to encourage such thought processes while teaching and assisting students with data processing and interpretation. Students were encouraged to report their data thoroughly and faithfully, with points awarded based on correct collection and interpretation of data, rather than obtaining the "right" data. Additionally, in the case of inspiration capacity measurements, students inadvertently exercised their lungs—which is the purpose of the incentive spirometers—during their practice attempts and repetitions. This immediate, personal feedback brought important significance to the lessons.

A word of caution: it is important to discuss and remind students of clinical measurement bias against minority populations and emphasize that individual data points should not form the basis of evaluating one's health, but that myriad factors contribute to one's health.⁵⁻⁷ While no such issues were made known to the TA, seemingly undesirable measurement results have the potential to negatively impact students' mental health and must be accounted for. This is not a novel issue. In-person lab experiments ask students to collect similar data for personal learning and analysis. However, the relevance of healthcare given the COVID-19 pandemic may have evoked deeper emotional responses from students compared to previous in-person labs. Personal relevance can work against student

education in extreme cases, and must be managed by the lab facilitator.

In the virtual format, students were never required to share their data with other students, the TA, or supervising faculty. No data was used for the purposes of this publication. However, students are encouraged to share data if they are comfortable doing so in order to compare subject-to-subject differences. This paradigm is comparatively more private than that of in-person labs, where students *must* work as a group in order to complete their experiments, naturally sharing their personally-collected data.

On Teaching Over a Virtual Platform

While the USC had used Blackboard Learn prior to the COVID-19 pandemic, switching to fully virtual lectures and labs has been a different challenge altogether. The short pre-experiment lecture was straightforward, enhanced by the full array of tools available on Zoom, including screen sharing, drawing, and markup tools. But a larger challenge was posed when demonstrating and running labs. Both the TA and the students were limited in what they could show the other. For the TA, demonstrating labs while talking through them required an awareness with body positioning within the webcam frame. While students were not required to perform the experiments live, the circumstances made troubleshooting experimental results difficult. Often, students were unable or unwilling to perform the experiments for the TA to observe and evaluate, but simply described the issue and their (often vague) observations.

Though there is no simple way to address these challenges, they can be mitigated greatly with TA preparation. The TA must be prepared to demonstrate strange and sometimes awkward motions on camera with confidence and must practice monitoring their camera feed when teaching and performing such actions. They should also have intimate knowledge of the experiments to better identify students' difficulties with minimal description. Building trust with students is also vital for facilitating what could otherwise be awkward demonstrations. Prerecorded video and images, especially publicly available resources such as YouTube, can be excellent supplements for students to easily review, reducing preparation time and providing clearer demonstrations. The use of instant-messaging (Slack) for communication with the TA also helped to facilitate "drop-in" office hours and fostered student engagement.

As we move closer towards resuming in-person instruction, we look to adapt the benefits of the at-home curriculum to supplement in-person instruction. Specifically, we believe that the use of manual blood

pressure measurements will help students better grasp the theory non-invasive blood pressure measurements compared to automatic measurements and should be kept post-pandemic. The at-home nature of the device also permits the longer-term data collection that cannot be easily accomplished with the traditional in-person curriculum. Student ECGs should be performed traditionally to provide important hands-on experience and troubleshooting. We also plan to add incentive spirometer measurements to be performed in tandem with traditional spirometer measurements. The latter provides useful insight into breathing patterns, but there is tremendous value in asking students to draw comparisons between low-cost, at-home devices and clinical devices. Similarly, heart rate measurements should be taken with a smartphone as well as a clinical pulse oximeter to elucidate differences between clinical and at-home methods of measuring heart rate.

Although the COVID-19 pandemic has forced the world to adapt in unforeseen ways, internet infrastructure can be powerfully leveraged to continue training biomedical engineers. The biggest challenge is restoring interaction and discussions between students. We believe the drawbacks posed by virtual learning are offset by advantages offered with innovative curriculum adaptation. When students return to the in-person classroom, it is our hope that the innovations due to virtual education will not be discarded as vestiges of a trying time, but rather as lessons to be incorporated to further improve the quality of biomedical engineering education.

AUTHOR CONTRIBUTIONS

VO TAed the class under SY, who provided the curriculum. VO modified the class according to student needs and wrote this manuscript, which has been reviewed and approved by SY.

CONFLICT OF INTEREST

The authors declare no competing interests.

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