JULY 01 2020

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American Journal of Physics 88, 526 (2020)
https://doi.org/10.1119/10.0001039

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Teaching the electrical origins of the electrocardiogram: An introductory physics laboratory for life science students

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(Received 26 June 2019; accepted 11 March 2020)

We present the design, pedagogical logic, and assessment of a laboratory and supporting materials that integrate a clinical academic cardiologist's understanding of the origins of the electrocardiogram (ECG) with a physics educator's insights into how to teach the underlying physics at the introductory level to life science students. In this article, we explain the choices made throughout the design process, connect a more advanced treatment of the physics to our approach, and present our assessment of the curriculum. Before the laboratory, students learn the cellular origins of the electric dipole potential produced by the heart on the body's surface, including a simple physical model for the electrical activity of excitable cells, and learn to interpret the measured voltages of an ECG as probing components of the heart's time-varying electric dipole moment. In the laboratory, students measure their own ECGs and analyze the data accordingly; they animate their data to display their own heart's dipole moment for a single heartbeat. Our results from the assessment of student understanding and attitudes indicate that although students find the content challenging, nearly all students find it at least moderately interesting, and for about a quarter of the students in the course, this lab plays a highly meaningful part in connecting physics to medicine.

https://doi.org/10.1119/10.0001039

I. INTRODUCTION: ELECTROCARDIOGRAPHY IN INTRODUCTORY PHYSICS FOR LIFE SCIENCE STUDENTS

As biological research and clinical medicine become more founded in an understanding of underlying physical mechanisms, the life science and medical communities have called for undergraduate life science and pre-medical students to gain a deeper understanding of the physical sciences and the ability to apply this understanding to the life and medical sciences. These calls have also emphasized the importance of students developing problem solving and mathematical skills.[1–3]

To address these needs, a national community of physics educators has developed a family of reformed introductory physics for the life sciences (IPLS) courses, which have demonstrated success in increasing the student appreciation of the value of physics for the life sciences and medicine.[4–6] These courses vary somewhat from setting to setting, to best meet the needs of their particular student populations and capitalize on their local strengths and resources, but most have a few goals in common as follows:

(1) to provide a coherent introduction to physics while presenting the topics most important for the life sciences and medicine, several of which are omitted from typical introductory physics syllabi;
(2) to support students to develop both a deep understanding of the core physical principles and strong quantitative problem-solving skills; and
(3) to cultivate in students the ability and motivation to model complex biological situations with physical principles, in part by making this a central repeated practice of the course.

Several articles have previously laid out general approaches to these courses,[5–8] and a new NSF-sponsored online curriculum database offered through AAPT[9] is designed to facilitate both sharing materials and supporting faculty in teaching a very different kind of introductory physics.

The course developed and taught for many years by one of the authors (CHC) introduces each unit and topic by describing an important biological or medical application, and then after presenting simpler examples to help students understand the topic, it culminates in analyzing that application.[6] This structure was developed based on the pedagogical frameworks of expansive framing[10,11] and cognitive apprenticeship.[12] We have found that indeed this course supports engaging student interest[4] and that the examples play an important role.[13]

The electrocardiogram (ECG (Ref. 14)) is a promising candidate for such a featured application. The ECG is of paramount clinical importance, being tremendously rich in information while also fast, inexpensive, portable, completely safe, and painless. The biophysics of the human heart's electric field is understood at the molecular level and is important for physicians to understand; a simple model of the origin of its electric field can be understood with introductory electrostatics, even though a full understanding requires a more advanced treatment.[15–18] In addition, the clinical ECG consists simply of 12 simultaneously measured time-dependent voltages; the measurement of voltages connects to students' basic understanding of DC circuits. Finally, measuring an ECG is sufficiently straightforward that students can do it in the laboratory with a moderately inexpensive, commercially available instructional apparatus.[19]

Nevertheless, teaching the electrocardiogram in a biomedically authentic[20] manner is fraught with pitfalls. The molecular and cellular biology producing the heart's electric field is not only extraordinary (and awe-inspiring to those so minded) but also sufficiently complicated that strategic decisions about simplification must be made. If the underlying physics producing the heart's electric field is to be taught, it must also be simplified. Consequently, it is challenging to develop a substantive study of the ECG that gives insights into both the biology and biophysics and is nonetheless accessible to introductory students and their instructors, who are physicists rather than physicians. Previously existing laboratories[21–23] that we are aware of focus on the apparatus and the measurement process rather than the underlying source of the electrical signal.

We set out to develop an authentic curriculum in which students learn the cellular origins of the electric dipole potential produced by the heart on the body's surface and learn to interpret the measured voltages of an ECG as probing components of the heart's time-varying electric dipole moment. We use a simple model to relate the electrical activity of an excitable cell to the charge dipole that students study earlier in the course.

One of the authors of this article (JWH) is a clinical academic cardiologist with nearly 50 years of experience teaching cardiology to medical students and clinical practice; the other (CHC) is a physicist with 20 years of teaching experience who has been a leader in the IPLS development community for more than 10 years. Collaborating to develop these materials was a lengthy, iterative process. First, CHC (the physicist) learned the cardiology as taught to medical students, and then, both authors worked together to develop and refine a laboratory centered around students measuring their own electrocardiograms and analyzing them in terms of the underlying physics. The laboratory was first offered in 2008 and reached its current form this year, with many successive refinements. The remaining materials were gradually developed to support the laboratory, as it became clear that a single lab meeting was insufficient for students to accomplish the learning goals.

Essential to this process was identifying and clearly articulating the essential physical principles at work, using an appropriate model accessible to life science students in introductory physics, in order to develop a task for students that required them to use those principles substantively to analyze their data.

In this article, we present the pedagogical logic behind the design of the materials so that other instructors can wisely teach and adapt our materials in their settings. All materials are freely available through the Living Physics Portal[9] and through the supplementary material of this article, with a Creative Commons license that allows use and adaptation with proper attribution. Section II provides an overview of the story line of the unit and the reasoning behind that story line; Sec. III fleshes out the primary approximation (treating a charge dipole as a current dipole) and its rationale; Sec. IV offers a few explanations of terminology that might be particularly confusing to physicists; and Sec. V offers our assessment of the materials.

II. PEDAGOGICAL DESIGN OF THE ELECTROCARDIOGRAPHY UNIT

We sought to provide students in an introductory physics course with the opportunity to learn the essential underlying principles of electrocardiography, although they will not fully understand it without medical education, subspecialty training, and clinical experience. From JWH's expertise, we identified the essential physical principles to be the following:

(1) the electric dipole moment of the heart (a vector, not just a magnitude) is probed by the many measured voltages of the electrocardiogram, and the full vector can be reconstructed;
(2) this dipole moment is produced by the flow of depolarization current through the heart tissue as it is activated.

These principles are central to the second-year medical student electrocardiography curriculum at the Perelman School of Medicine, qualifying them as "authentic"[20]—in other words, physicians who are experts in electrocardiography, not just physicists, consider these essential to understanding the electrocardiogram.

From having identified these principles, we designed this unit to prepare students to answer the following two questions:

- Why does the heart produce a moving electric dipole moment? ("Moving" here means time-dependent in both the magnitude and direction.)
- How does the electrocardiogram measure that moving dipole moment?

We also wish to address two questions that in CHC's experience typically follow:

- How do measurements of the moving dipole moment reveal heart disease?
- Why is the heart's electric field so much greater than those produced by other muscles or the brain, all of which are made up of electrically active cells?

To address these questions, we wrote a reasonably brief introduction to the molecular and cellular biophysics of the heart that answers these questions in a simplified manner and is fully accurate, although incomplete. This introduction presents the following sequence of ideas:

(1) Muscle cell contraction is activated by cell membrane depolarization. A muscle cell contracts when its membrane is depolarized and relaxes when it repolarizes.
(2) The flow of current associated with depolarization produces a moving electric dipole moment, which in turn produces a changing electric field on the body's surface.
(3) Because the dipole moment comes from the current that flows during depolarization or repolarization, there is zero dipole moment and thus zero electric field whenever no depolarization or repolarization takes place, including during the time between depolarization and repolarization.
(4) In the heart, for each heartbeat, depolarization initiates in a small region, normally the sinoatrial node, and spreads throughout the entire heart in a highly coordinated fashion. Repolarization occurs after a significant delay.
(5) As depolarization spreads across the heart, the heart's total electric dipole moment at any instant in time is the vector sum of all of the dipole moments of the individual parts. Because the cells are not all activated simultaneously but are activated in an exquisitely timed sequence in order for the heart to function, this total dipole moment changes both the magnitude and direction throughout a single heartbeat.

(6) This coordinated wave of depolarization, combined with the delay before repolarization (which is longer in cardiac muscle cells than in other cell types), causes the heart to be the dominant source of the electric field on the body surface.
(7) The electrocardiogram measures multiple distinct potential differences on the surface of the body as a function of time. For each measured potential difference, the two electrodes are roughly equidistant from the heart and on opposite sides of it. Consequently, each potential difference is proportional to the component of the heart's electric dipole moment along the axis on which it is measured; its time dependence reveals how that component changes due to the movement of the dipole moment. The entire moving dipole moment can be reconstructed from the measured set of potential differences.
(8) Disrupting the sequence of electrical activation, or changing the heart's structure, changes the magnitude, direction, and/or time dependence of the heart's dipole moment vector significantly, giving the ECG its diagnostic power.

This outline implies, though does not state explicitly, that the heart's dipole moment vector is a charge dipole. In fact, it is actually a current dipole but can be modeled as a charge dipole due to some beautiful and nontrivial physics beyond the introductory level.[15,16] In Sec. III of this article, we discuss the physics and pedagogy behind this approach.

Point 7 arises from a nontrivial property of the electric potential field of dipoles. As shown in Fig. 1(a), because the perpendicular bisector of the dipole is an equipotential, a horizontal dipole moment produces potential differences between locations on the horizontal axis, such as ΔV_{12}, which are proportional to that dipole moment, but potential differences between locations on the vertical axis bisecting the dipole, such as ΔV_{34}, are all identically zero. Likewise, a vertical dipole moment produces potential differences between vertical locations and zero potential difference between horizontal locations (Fig. 1(b)). Generalizing this to an arbitrary coordinate system, because the dipole moment can always be represented as the vector sum of two perpendicular components, the potential difference between any two points located symmetrically on either side of the dipole is proportional to the component of the dipole along the axis between those points, as illustrated in Fig. 1(c). This is true for any arbitrary axis, not only for the x and y axes illustrated in the figure, so any electrocardiography measurement probes the component of the dipole along the axis defined by the measurement.

The introductory reading does not present the mathematical derivation, as we find this is the most difficult part of the argument for life science students, who are far more comfortable with conceptual discussions and biological complexity. Instead, we present the derivation as part of an interactive lecture preceding the laboratory, which emphasizes the conceptual takeaway: a potential difference measured along a particular axis probes the component of the dipole moment along that axis. We also provide a written version of the derivation for them to review afterward along with a homework problem. This derivation could instead be incorporated into the reading if desired.

At the start of the laboratory, students engage with the underlying logic of the derivation in a tutorial-style[25] conceptual activity, which connects back to the previous week's laboratory (mapping equipotentials produced by various arrangements of electrodes[26]).

Students subsequently use the result of the derivation to analyze their experimentally measured electrocardiographic data. To emphasize the key idea that the heart produces a dipole moment that varies with time in both the magnitude and direction, students use their data to calculate the time-dependent dipole moment of their own heart, first at a few selected time points and then by animating their analyzed dataset to display the vector dipole moment throughout a single cycle, using an instructor-written Mathematica notebook that students just need to run.

To give medical context to the derivation, the interactive lecture precedes it by reviewing the highlights of the reading and follows it with opportunities for students to apply their understanding of the electrocardiogram through carefully scaffolded ConcepTests[27] (also called think-pair-share activities or clicker questions[28]) based on examples of diseased electrocardiograms.

III. MODELING A CURRENT DIPOLE IN AN IRREGULAR CONDUCTING MEDIUM AS A CHARGE DIPOLE IN AN INFINITE DIELECTRIC MEDIUM

The major simplification of the physics we use is to treat the heart's dipole moment as a charge dipole when it is in fact a current dipole. In other words, the dipole moment of each wave of depolarization does not correspond to a closely spaced pair of oppositely charged particles moving in tandem, as represented in the figures in the reading, but actually represents a closely spaced source and sink of current. Here, we justify for instructors why the heart's current dipole moment can be well modeled by a charge dipole and explain the limitations of this model.

The human body is a good conductor, except for the skin. As a junior-level electricity and magnetism course with the tools to solve boundary-value problems can demonstrate, current sources and sinks in a conducting medium are described by exactly the same mathematics as charged particles in an insulating medium.[15,16,18] Consequently, if the body was a uniform spherical conductor, the electric field produced by the heart's current dipole would be exactly what would be expected for a charge dipole embedded in a spherical insulator.

Because the body is not uniform and is of irregular shape, the electric field of the heart propagates somewhat nonuniformly through the tissue to the surface of the body. Surprisingly, the surfaces of the limbs turn out to be nearly equipotentials, with most of the variation in potential occurring on the surface of the torso. (For this reason, students can affix electrodes to either their wrists or their elbows, without significantly altering the measured electrocardiograph. The original electrocardiogram pioneered by Dutch physiologist Willem Einthoven, for which he won the 1924 Nobel Prize in Physiology or Medicine, made electrical contact to the limbs by putting the patient's hands and feet in tubs of salt water.[29]) Calculating the quantitatively exact relationship between the heart's time-varying dipole moment and the resulting surface potentials would thus require detailed computational modeling.

Instead, we choose to quantitatively take the approach that is invoked qualitatively in teaching electrocardiography to

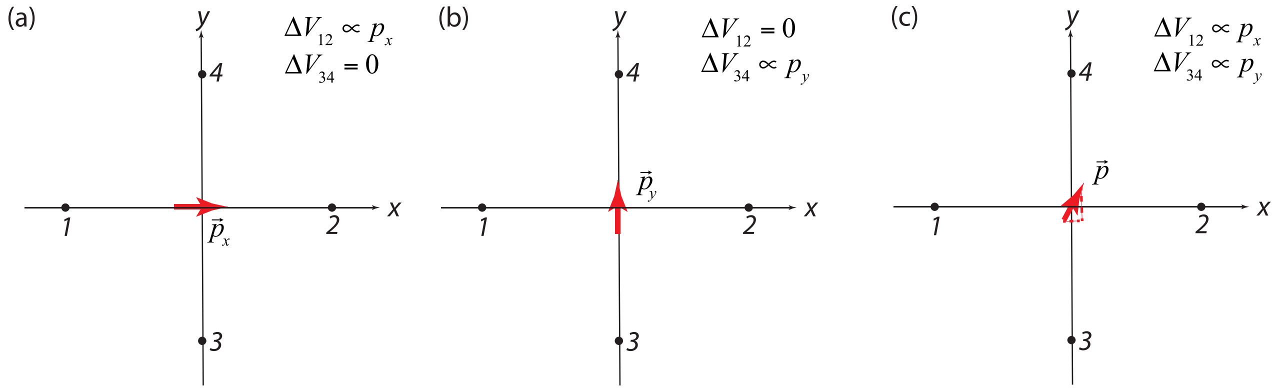

Fig. 1. As proved in the derivation in the instructional materials (supplementary material; Ref. 24). (a) The potential difference measured symmetrically on either side of a horizontal electric dipole is proportional to the dipole moment, and the potential difference along a vertical axis is zero; (b) likewise. (c) The potential difference measured between two points located symmetrically on either side of a dipole along any axis is proportional to the component of the dipole along that axis. (The figure shows this for horizontal and vertical axes, but it is true for any arbitrary axis.)

second-year medical students; we model the electric field and potentials produced by the heart's dipole moment as simply being that of a moving charge dipole embedded in an infinite dielectric medium. Students in this course do not have the mathematical tools to solve boundary-value problems, and we judge that our course lacks the time to study current sources and sinks. We also neglect inductive effects associated with the movement of the dipole (we use the quasistatic approximation), which is very reasonable given the slow timescale of the changes (major features in the electrocardiogram range from several to tens of milliseconds in duration).

Although in general in our IPLS course, clearly stating approximations is a skill we seek to develop in our students, in teaching electrocardiography, we do not mention these approximations except in a single footnote in the reading. We make this choice because, unlike the approximations we teach students to make consciously in our course, the approximations required here are beyond the scope of the course, and we do not feel the students would be served by knowing the details, except for the rare individuals who inquire.

Due to all of these approximations, the mathematical derivation that provides the foundation for calculating the heart's dipole moment is not quantitatively accurate. Nevertheless, we feel the time-dependent dipole moment calculated with these approximations still qualitatively reveals the key features of the heart's activity, and thus, there is still value in the students going through the analysis and visualizing it.

In our opinion, the only truly questionable aspect of the analysis is instructing students to compare the maximum amplitude of their measured dipole moment to a typical dipole moment of a polarized molecule. They find that their measured dipole moment is many orders of magnitude larger than that of even a water molecule (the largest physiologically relevant permanent molecular dipole moment), consistent with the key concept that the dipole moment of the heart is the vector sum of many individual depolarizing muscle cells throughout the heart tissue. Because the underlying dipole is current, not charge, and the instrumentation affects the measured value of the voltages, there is no real physical meaning in the numerical value the students obtain for the dipole moment, so it is somewhat dubious to interpret it.

In spite of this, we include this task in the analysis because an important goal of our course is for students to reflect on the reasonableness of measured and calculated values. The dipole moment is an important quantity; as it happens that the value obtained this way is consistent with the simple model, making this comparison gives students practice thinking about the quantity of the dipole moment, including its units. Nevertheless, in the Instructor Notes, we call attention to this shortcoming, and instructors who prefer not to include this part of the analysis can omit it.

IV. VOCABULARY AND TERMINOLOGY

A significant challenge for physicists trying to learn and teach biomedical physics is the substantial amount of unfamiliar vocabulary. In our materials, we have tried to use life science vocabulary when needed, explain it clearly, and reassure students that they are not expected to memorize this vocabulary; it is provided so that any students who have encountered this topic in another context can make the connection.

Another challenge is terms that are used differently from how physicists would use them, or in ways that are nonintuitive to physicists. Below we describe the most important of these differences. We strongly encourage physicists not to criticize physicians for using different terminologies but simply to point out these differences to students so that they can be alert to them and to remark that it is not uncommon for different fields to develop different terminologies.

- Leads: in medical parlance, each one of the twelve measured potential differences of the clinical ECG is called a "lead," as in "the Lead I voltage." A physicist might prefer to refer to this as a pair of electrical leads, as two contacts are needed to measure a voltage. (Note that physicians also refer to the individual electrical contacts in the pair as "leads," so the term lead can refer to either a pair or one of a pair.)
- Membrane potential: in electrophysiology, the "membrane potential" refers to the electric potential of the interior of the cell, with the zero of potential taken to be in the extracellular space. A physicist might instead call this "the potential difference across the cell membrane." Also, while a physicist might consider it inconsequential to reverse the polarity of the measurement, this would defy long-established conventions in electrophysiology of always choosing the reference of potential to be outside the cell (the "extracellular space"), as is experimentally

practical. In most of our ECG teaching materials, this is not directly addressed because discussion of the membrane potential takes place earlier in our course, and so, we have already clarified this. In our course, after directly discussing what physiologists and cell biologists mean by membrane potential and relating it to the physics, we use that term relatively little and typically use specific mathematical notation, to minimize confusion.

V. ASSESSMENT AND DISCUSSION

To evaluate what students take away from this unit, we gathered three types of data:

- Students wrote a 300–500 word explanation of the central principles of the ECG as the conclusion to their lab book.
- The midterm and final exam included multiple-choice questions that probed their understanding of the potential differences produced by electric dipoles.
- We documented students' affective responses to the laboratory through course evaluation responses and an end-of-semester writing assignment.

In brief, we find

- About half of our students wrote coherent, reasonably accurate, and detailed summaries of the key concepts of the electrocardiogram, and about 30% wrote adequate summaries, although few wrote a summary that displays highly sophisticated understanding. We feel that this indicates reasonable success of our instruction, given the complexity of the science involved and the limited time devoted to it.
- On the midterm, 68% of students correctly answered the relevant question, and another 18% gave the correct answer up to reversing the dipole moment, a very understandable error given that the opposite sign convention is frequently used in introductory chemistry.[30,31] However, on the final, only 35% gave the correct answer and 18% the reversed answer, which may reflect the decline of their understanding with time, mathematical difficulties with the structure of the question, or both. Although we would have been more encouraged by better performance, the analysis of the potential produced by a dipole, particularly the vector analysis involved, is among the more abstract and challenging topics in the curriculum, so it is not surprising that the students found the final exam problem difficult.
- Interest rankings on the course evaluations and the writing assignment indicate that 90% of students found the lab at least somewhat interesting, and over the last three years, for roughly a quarter of students, it was among the most memorable and meaningful connections provided between physics and the life sciences. We consider this highly successful given the challenging nature of our treatment, the relatively brief time the students have to learn this material, and the lack of direct connection to what students are learning in their other courses.

A. Student work on written summary

At the conclusion of the laboratory, we gave students the following writing assignment prompt:

> The goal of this exercise is to help you consolidate your understanding of electrocardiography by summarizing the key ideas. Writing a good summary is challenging, so we provide specific guidance on how to do so. Write a brief narrative explanation of electrocardiography for a hypothetical friend who took PHYS 004L several years ago, before this lab was introduced, so they have learned the basic physics, but it is not fresh in their mind, and they have not studied electrocardiography. In a total of 300–500 words, spending about 20 min, explain
>
> - Why does the heart produce an electrical signal?
> - What is the measurement that makes up an ECG and how does it reveal what is going on in the heart?
>
> If you wish, you can include mathematics and sketches as part of your explanation, but you should write a coherent set of several paragraphs. It is not required to include math or sketches. If you wish to include a sketch, please turn in a printout of your text with the sketches added and also upload a photo of what you turn in. If you include math in your explanation, you can use bold type to indicate vectors.

There were no restrictions on students accessing resources as they wrote the summary. However, none of the summaries appeared to be simply assemblies of statements copied and pasted from the lab documents. We expect that some combination of the low-stake nature of the grading (full credit for reasonable effort) and the explicit instruction to spend only 15–20 min on it minimized the number of students who consulted resources extensively.

Among the 57 students enrolled in the course, 55 submitted summaries. We analyzed the summaries by scoring them according to a five-item rubric developed by CHC based on her own written response to the prompt. The rubric items correspond to the elements of a complete explanation corresponding to the material taught in the course and are provided in the left column of Table I. Each summary was given a score of 0, 1, or 2 for the item being absent, partially present/correct, or fully present/correct.

Each summary was also given a score for overall coherence and clarity. Of the 55 summaries, 13, or 24%, received a coherence score of 0 and were omitted from further analysis. Of the others, 16 (29%) received a coherence score of 1 (moderately coherent) and 26 (47%) received a coherence score of 2 (highly coherent). As can be seen in Table I, the highly coherent responses earned higher average scores on each item than the moderately coherent responses.

All summaries were scored by CHC, with a second researcher independently scoring 16 of the summaries, three of which were excluded due to the lack of coherence. After comparing scores and adjusting the rubric to clarify how it was to be used, the two researchers either completely agreed or agreed within 1 point on all 13 of the remaining summaries. The scores are reported in Table I.

We totaled the scores on the five items to give an overall completeness and correctness score, with a maximum value of 10. For the 26 highly coherent summaries, the average completeness/correctness score was 7.4. Of these 26 summaries, four earned the maximum score of 10, three earned 9, and seven earned 8. Four earned scores of 5 or less, corresponding to students who interpreted the assignment significantly differently than we intended, but nonetheless wrote a

Table I. Rubric and results from student summaries in response to prompt provided in text. Of 57 students in the class, 55 submitted summaries; only those which were highly coherent or somewhat coherent were scored.

Item	Average score	Number earning that score		
		Absent (0)	Partly present/correct (1)	Fully present/correct (2)
Cardiac muscle cells depolarize as they contract.	…	…	…	…
Highly coherent responses (N = 26)	1.73	0	7	19
Moderately coherent responses (N = 16)	1.44	0	9	7
The moving depolarization front corresponds to a moving electric dipole.	…	…	…	…
Highly coherent responses (N = 26)	1.65	3	3	20
Moderately coherent responses (N = 16)	1.13	3	8	5
The heart's electric dipole moment is the vector sum of the dipole moments of the constituent cells.	…	…	…	…
Highly coherent responses (N = 26)	1.23	6	8	12
Moderately coherent responses (N = 16)	0.63	6	10	0
The ECG measurement consists of several potential differences on the surface of the body.	…	…	…	…
Highly coherent responses (N = 26)	1.65	4	1	21
Moderately coherent responses (N = 16)	1.56	1	5	10
Each potential difference is proportional to the component of the heart's dipole moment along the measurement axis.	…	…	…	…
Highly coherent responses (N = 26)	0.96	10	7	9
Moderately coherent responses (N = 16)	0.81	4	11	1
Total score (maximum 10)	…	…	…	…
Highly coherent responses (N = 26)	7.38	…	…	…
Moderately coherent responses (N = 16)	6.00	…	…	…

coherent discussion. For the 16 moderately coherent summaries, the average completeness/correctness score was 6.0, with the individual scores ranging from 3 to 8, indicating that on average, the less coherent summaries were also less complete and correct. Between the moderately and highly coherent summaries, 28 of 55 earned a score of at least 7.

We take these scores as an indication that roughly half of the students achieved a significant grasp of the material (corresponding to a score of 7 or more), and many others achieved some grasp, which we consider to be moderate success at helping students understand some very complex and abstract physics as the basis of electrocardiography. Clearly, there was variation in how students interpreted the assignment, and omission of a particular item in the rubric may have reflected student interpretation as much as understanding; for example, four students wrote highly coherent summaries that were fully correct as far as they went but earned scores of 5 or less, typically failing to describe the measurement and focusing on the activity of the heart.

The two individual items on which the scores were the lowest were "The heart's electric dipole moment is the vector sum of the dipole moments of the constituent cells" and "Each potential difference is proportional to the component of the heart's dipole moment along the measurement axis." In the case of the vector sum item, there were a few examples of summaries in which the student never talked about the depolarization of individual cells but talked specifically about a depolarization wave spreading across the entire heart. Although this was not the approach we took, this is a reasonable approach used by other sources, and so, we awarded 1 point (partly present/correct) for this approach. We also awarded 1 point if students in some way described the depolarization of individual cells and then described the electrical activity of the entire heart as highly coordinated or synchronized, without using explicit vector sum language. The low score overall on this item may reflect a lack of understanding by students; it could also reflect an assumption that if they explained what was happening in an individual muscle cell, it was obvious that the heart's total electrical signal came from combining that of the individual cells. Further work would be needed to distinguish these possibilities.

With average scores below 1 from both coherence categories, "Each potential difference is proportional to the component of the heart's dipole moment along the measurement axis" was the item on which students scored the lowest, even though students used that relationship to analyze their data. Of the 14 summaries that earned 0 on this item, 10 nevertheless described determining the heart's dipole moment from the ECG but without connecting the potential difference measurements explicitly to dipole moment components. Again, we do not have enough information to determine if the low scores reflect a lack of understanding or a different interpretation of the question. Some students might not think of including this technical relationship when explaining "What is the measurement that makes up an ECG and how does it reveal what is going on in the heart?" and these same students might be able to state it in response to a more specific question.

B. Midterm and final exam problems

The problems asked on the midterm and final exams are given in Fig. 2.

Both problems probe the key physical idea that a potential difference in the field of a dipole is proportional to the component of the dipole moment along the axis of the potential difference measurement and also require the student to correctly reason about the polarity of the dipole and the potential difference. Although rather technical, CHC and the

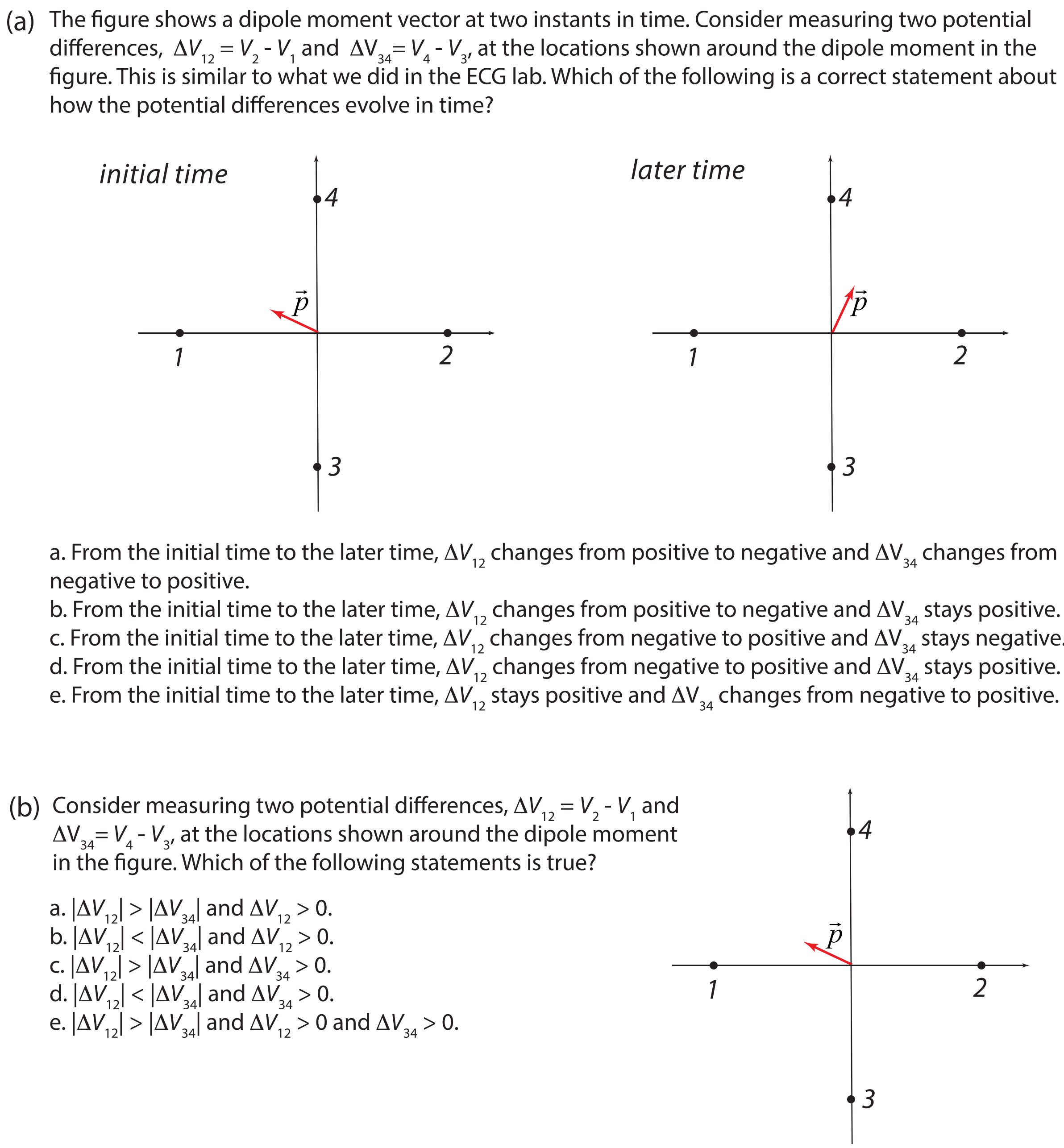

Fig. 2. Problems given to assess the physics of ECG on (a) the midterm exam and (b) the final exam.

course instructor designed this problem to test only the physics, not the biology, so that students with differing amounts of the biological background would not be at a disadvantage or advantage.

On the midterm exam, 68% of students (39 out of 57) correctly chose answer E, and another 18% (10 students) chose answer B, which is correct up to reversing the polarity of either the dipole moment or the potential difference measurement. In our experience, students commonly reverse the dipole moment, as the convention typically used in introductory chemistry[30,31] is the reverse of that used in physics, defining the dipole moment to point from positive to negative. The average score on all of the multiple-choice items on the midterm was also 68%. It is noteworthy that students had previous years' midterms to guide their studying and to use as practice tests, and this question was the only one on a topic that did not appear on the earlier midterms, although electrocardiography was listed on the list of topics that the midterm might cover. Consequently, we consider students to have been quite successful in answering this question.

Scores were lower on the final exam, possibly because the material was more remote in time or because the problem as written required more mathematical fluency. Only 35% of students (20 of 57) gave the correct answer (C), with another 18% (25 students) giving the correct answer up to a reversal of the dipole moment (answer A). Some student scratch work suggested that some students may have struggled to grasp the answer statements due to the absolute values. We have noticed in recent years that the number of students lacking fluency with all but the most common mathematical notation is increasing. The average score on the final exam multiple choice questions was 70%, so this question was one of the most difficult for these students. Again, it was the only topic for which there were no corresponding questions on previous years' exams.

Although the decline of performance on the final exam sobers, it is not surprising that students were less successful on the final exam, about two months after doing the lab, and then, they were on the midterm only a week later. To understand better how much students understood at both stages would require open-ended tasks that could distinguish mathematical from physical understanding. We are pleased that nonetheless, 35% of students correctly answered the task.

C. Affective responses from course evaluation and end-of-semester writing assignment

From 2012–2018, on the end-of-semester course evaluation, students were asked to indicate their level of interest in each of the most prominent biological applications, using a five point Likert scale (1 = not interesting at all and 5 = of great interest). For ECG, the average score over all seven years was 3.8. Averaged over all seven years, roughly 65% of students rank it 4 or 5, roughly 25% of students rank it 3, and the remaining 10% rank it 1 or 2. Although these percentages remain approximately stable throughout the time period, during 2012–2015, there were consistently more rankings of 4 than 5, while in 2016–2018, this was reversed (with a slight increase in the number of 3 and 2 rankings keeping the average score fairly steady). These rankings indicate that consistently 60%–65% of students have found the lab of significant interest (ranking 4 or 5), with the fraction of students giving it the highest rating increasing in the last few years. In comparison to all biological applications that students ranked, ECG typically fell in the middle of the rankings.[13]

We have no direct information about what might have caused the number of rankings of 5 to increase. In 2016, the instructor began to devote a modest amount of class time the previous week to explaining the basic physics, rather than presenting it all in the prelab lecture the day of the laboratory; this may have helped students absorb this complex topic, by giving them more time to digest it, although the total instructional time remained roughly constant.

At the end of the semester during 2017–2019, students reflected on the entire course in a written assignment, in response to the following prompt:

> Write a non-technical "letter home," in which you describe to a friend or relative what was significant to you about PHYS 004L. You should assume your friend or relative is not a scientist, so you shouldn't use a lot of jargon or technical terms unless you explain them. Use your own voice and imagine that you really are writing to someone you know. (You don't have to actually send the letter unless you want to!) Respond specifically, and in a total of 500-ish words, to these two prompts:

- In what way(s) was 4L an interdisciplinary course? What interdisciplinary examples stand out? Be specific.
- What skills or ways of thinking did you develop or deepen during the 4L semester?

This assignment thus gave students the opportunity to reflect back over the entire course and identify only the examples that were highlights for them personally, without prompting with a list of examples or requiring them to react to any particular ones. Over those three years, roughly a quarter of the students in the course mentioned ECG as among the standout examples (36 of 152 who submitted letters).

Although some students listed all medically related applications as significant without elaborating, others wrote about the ECG unit in great detail. These students describe this example as highly meaningful for them. For example, one student wrote:

> *The most interesting experience I had in the class was the time we measured the difference in potential on the surface of the human body that is generated by the activity of the heart. I never imagined having electrodes hooked to my wrist and ankle and measuring an electrocardiogram in a Physics lab! That day, it really struck me how closely medical concepts are related to those in physics. Before that experiment, "physics" would not be an answer I have off the top of my head if someone asks me what area of knowledge I'd have to have in order to understand cardiology, but that certainly changed.*

Another student wrote:

> *Before this class, I was truly ignorant [of] how our hearts produce those peaks that appear on electrocardiogram results. It was really interesting to learn that our hearts produce electrical signals that were then captured by the electrocardiogram machine. That experiment also helps me to understand more about how our body—our heart—works. It is fascinating to learn about how our heart, which is much smaller as compared to the size of our body, could pump blood around the body. The electrical signals need to be coordinated in order for the heart to be able to pump blood effectively. I would not have guessed that this is the case, before taking this course.*

All of these results indicate that in spite of the complexity of the physics, 90% of students in the course find the study of the ECG at least moderately interesting (ranked it at least 3) and over 60% ranked it 4 or 5, with the number of students ranking it 5 increasing in recent years. In addition, about a quarter of students chose to highlight it in their final written assignment. We conclude that in addition to nearly all students finding it moderately interesting, for a substantial minority of students, the ECG lab is highly significant. This is perhaps all the more noteworthy because of the relatively modest time devoted to it and the difficulty of the underlying physics. The examples receiving the highest interest rankings, such as cell membrane potential and nerve signaling,[13] are indeed the most commonly mentioned examples in these letters home. However, these all appear repeatedly over multiple weeks of the course and/or have significantly more instructional time devoted to them; the physics is also more straightforward than the physics of the potentials produced by electric dipoles.

VI. CONCLUSIONS

This article presents the pedagogical logic of our ECG lab and supporting instruction in an introductory physics for life sciences course in which students learn the key principles of electrocardiography, although with some simplifications. We have selected the essential ideas taught in order to highlight the connections to basic physics, while being congruent with how the electrocardiogram is taught in medical school and how it is understood by physicians who specialize in interpreting electrocardiograms. Similarly, we have chosen the simplifications so that if students go on to study medicine, they will not feel that they have to overcome previous wrong understanding but rather that they will be filling out and adding details to a sound though elementary understanding.

Our assessment indicates that while students find the topic difficult, many students are able to write a moderately good summary, and a significant minority finds the experience of doing the lab highly significant in demonstrating the central nature of physics to medical science. We are glad to have the opportunity to share the astonishing elegance of the heart's electrical system with these students.

ACKNOWLEDGMENTS

C.H.C. gratefully acknowledges the essential partnership of Mary Ann Klassen (senior lab lecturer at Swarthmore College) in teaching this lab at Swarthmore since 2008. She thanks Ben Geller for many useful conversations, developing the first version of the Powerpoint slides for the interactive lecture, and helps with data analysis; Peter Collings and Adam Light for helpful feedback on the manuscript; Russ Hobbie for helpful conversations; and Amy Crouch for help with illustrations. Both authors thank Dr. Yale Goldman and Dr. Lawrence Frame of the Perelman School of Medicine of the University of Pennsylvania for sharing the materials they use for teaching electrocardiography in the medical school curriculum.

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