Electrocardiography (ECG) is one of the most widely used methods in clinical diagnosis. Here we describe an experimental approach that offers hands-on learning of its basic principles. An experimental model that consists of a rubber foil with a low electrical conductivity and a DC power unit is used to simulate the body and the electric dipole of the heart. It enables students to learn about the main features of the electric dipole and to visualize the induced electric potential in the body. The determination of the characteristic equipotential lines around the dipole and the measurement of simple electrocardiograms, comprising bipolar and unipolar leads, are made with a low-cost voltmeter. To make the exercise more relevant to clinical ECG, as well as making it more interesting, the students are additionally tasked to measure their own electrocardiogram with a simple, personal handheld ECG device.

**INTRODUCTION**

Electrocardiography (ECG) has become one of the basic diagnostic tools in medical practice (9). Since its invention at the beginning of the twentieth century, it has facilitated enormous advances in the technical and diagnostic fields (3). This progress can be easily demonstrated by comparing the 300-kg ECG device used a hundred years ago with the size and capabilities of ECG machines used in a modern clinical environment. Back then, an electrocardiograph occupied two rooms and needed five people to operate it (7). Today, understanding the basic physical principles of ECG remains a challenge for the typical medical student, who lacks a strong background in physics.

The curriculum of a medical student involves several practice-oriented ECG courses. However, they all address the topic on a significantly higher, more sophisticated or practice-oriented level (10). Hands-on experiments used to illustrate the basics of ECG at the preclinical level are less common. Two prominent examples are simple electrical setups that have been used to illustrate the principles of ECG measurements within the framework of the Einthoven triangle (2, 7). In this article, we briefly describe a simple, low-cost experimental ECG model, and corresponding experiments, which takes the learning of ECG concepts one step further from a basic illustration of the Einthoven triangle. In particular, the approach presented enables students to measure and visualize the changing electric potential within the body, which is invaluable when the student strives to relate the electric dipole of the heart to the ECG readings. In addition, the setup demonstrates that the electric dipole of the heart is a source of electric currents in the body, which guides the student away from the simple notion of an electrostatic dipole of the heart toward a more realistic current dipole arising from the polarization/depolarization waves in the heart muscle. Finally, the experiments with the ECG model are supplemented with a measurement using a simple, personal one-lead ECG device, which demonstrates a real ECG reading and allows the student to verify some of the learned concepts (e.g., that the electrocardiogram turns upside down if the electrodes for the right and left arm are interchanged or that the recorded signal depends on the electrical contact between the patient’s skin and the electrodes).

**EXPERIMENTAL SETUP**

The experimental setup comprises an ECG model representing the human body, a custom-made DC power unit, two digital multimeters, and a simple, handheld, one-lead ECG device (Fig. 1A). The ECG model consists of a rubber foil mounted on a wooden plate. The foil is carbon-doped to obtain a resistivity comparable to that of the human body, i.e., ~1 kΩ cm (1). Nine electric connectors are built into the model: six of them, placed in a circular layout, are used to simulate the heart dipole, and three of them represent the outputs, the – inputs.

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**Teaching the basic principles of electrocardiography experimentally**

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Abstract

Electrocardiography (ECG) is one of the most widely used methods in clinical diagnosis. Here we describe an experimental approach that offers hands-on learning of its basic principles. An experimental model that consists of a rubber foil with a low electrical conductivity and a DC power unit is used to simulate the body and the electric dipole of the heart. It enables students to learn about the main features of the electric dipole and to visualize the induced electric potential in the body. The determination of the characteristic equipotential lines around the dipole and the measurement of simple electrocardiograms, comprising bipolar and unipolar leads, are made with a low-cost voltmeter. To make the exercise more relevant to clinical ECG, as well as making it more interesting, the students are additionally tasked to measure their own electrocardiogram with a simple, personal handheld ECG device.
but also in a continuous medium such as human tissue. They also learn that the current is proportional to the voltage, i.e., the heart dipole induces an electric current in the tissue. In this way the students are then encouraged to change the output voltage on the DC unit and to examine the relationship between the voltage applied on the poles and the electric current flowing through the body, measured by the supplied voltmeter and ammeter. In this way the students learn that in an electrically conductive human body the supplied voltmeter and ammeter. In this way the students learn that in an electrically conductive human body the induced electric current is proportional to the voltage, i.e., so that the measured electric potential stays at a certain value (Fig. 2A). In this way the characteristic equipotential lines with values equal to 0 mV, 20 mV, 40 mV, as well as −20 mV and −40 mV are determined.

The students are then asked to draw the determined equipotential lines on graph paper, together with annotated positions of the connectors (Fig. 2B). To visualize the equipotential lines and to become more familiar with the relation between the dipole orientation and the potential induced in the body, the students have to imagine how the characteristic equipotential lines would change if the “heart” dipole is rotated to the second orientation (\(\uparrow\downarrow\), red). By drawing the lines around the rotated electric dipole (Fig. 2C), the students learn how the induced equipotential lines passing through a certain point on the body change with the changing electric dipole. In particular, they realize that the two arms [left (LA) and right (RA)] are at the same potential when the dipole is in the vertical orientation (\(\uparrow\)) and that the same is true for RA and the left leg (LL) when the dipole is in the diagonal orientation (\(\uparrow\downarrow\)), etc. This is the basis for understanding the ECG signal in a human body.

Task 3. Measurement of a Simulated ECG Signal in the Model

After the students get acquainted with the meaning and the shape of the equipotential lines, the ECG model is used to measure a simplified ECG of the three standard bipolar leads, i.e., the voltages between the points representing the left arm (LA), the right arm (RA), and the left leg (LL), which are equal to the differences between the equipotential lines passing through these points. The changing electric dipole of a beating heart is simulated by changing the orientation of the “heart” dipole on the ECG model. The orientation of the heart dipole is changed in a clockwise direction by stepwise changing the positions of appropriate pairs of “heart” connectors on the ECG model (the orientations \(\uparrow\), \(\uparrow\downarrow\), \(\downarrow\), \(\downarrow\uparrow\), and \(\downarrow\) in Fig. 1). In this way the “heart” dipole with the same magnitude and different orientations is obtained.

To measure lead I, for example, the voltage between the left arm (LA) and the right arm (RA) is determined...
stepwise at all orientations of the “heart” dipole. The students then draw the measured ECG on graph paper (Fig. 3A, top) and reflect on the relation between the dipole orientation, the potential in the body, and the ECG readings. They can verify that the ECG readings are close to zero when the dipole is perpendicular to the line connecting the limb electrodes (e.g., when the 2 measuring electrodes are at the same potential, as seen in the previous task) and

![Figure 2. Measurement and visualization of the equipotential lines. A: the experimental procedure. The “heart” dipole is set by connecting the vertical (blue) connectors on the electrocardiography (ECG) model to the + and – outputs on the DC power unit. The negative pole of the voltmeter (COM) is connected to the neutral output (0 mV) on the DC power unit, and the positive pole is connected to the probe. To find the points of constant voltage, the probe is moved along the rubber foil (in the case presented, the equipotential line with –20 mV is sought). The action is schematically indicated by the dashed blue line with the arrow. B: the measured characteristic equipotential lines with the heart dipole in the vertical orientation (⊥) are drawn with solid blue lines on graph paper. The positions of the connectors on the ECG model are also depicted. Because in this dipole orientation the left (LA) and right (RA) arms are at a similar potential, we would expect that the ECG reading for lead I (RA-LA) to be close to zero. C: the predicted equipotential lines with the “heart” dipole in the diagonal orientation (\(\diagup\)) are visualized with dashed red lines. In this dipole orientation, the reading of the lead II [RA-left leg (LL)] will be close to zero.](image)

![Figure 3. Electrocardiograms obtained with the electrocardiography (ECG) model and the handheld ECG device. A: a typical measurement of the 3 bipolar leads (top) and a typical measurement of a unipolar lead (bottom) with the ECG model. The measured voltages are drawn as a function of the orientation of the heart dipole. As predicted in task 2, the bipolar lead I is zero in the vertical dipole orientation and the bipolar lead II is zero in the diagonal dipole orientation (see Fig. 2). The directly measured unipolar lead VF (blue) is compared to the calculated augmented unipolar lead aVF (red). B: electrocardiograms measured with the handheld ECG device under normal conditions (top) and with interchanged thumb positions on the electrodes (bottom). The latter is flipped upside down.](image)
a maximum when the dipole orientation is approximately parallel to that line.

Optionally, the ECG model can also be used to determine the unipolar leads. The unipolar ECG leads measure the potential of three limbs relative to the potential at infinity, i.e., to zero potential (8). With this setup they can be measured directly according to their definition, i.e., by simply measuring the voltage of the limbs relative to the zero potential on the DC power unit. In practice, the zero potential is approximated by the mean potential of all the limb electrodes (Wilson central terminal) or by the mean potential of two opposing limbs (Goldberger augmented unipolar leads aVR, aVL, and aVF). In the latter case, the unipolar leads can be calculated from the bipolar leads I, II, and III with the equations

\[
\begin{align*}
\text{aVR} &= -(I + II)/2 \\
\text{aVL} &= (I - III)/2 \\
\text{aVF} &= (II + III)/2
\end{align*}
\]

The students can easily verify that the augmented unipolar leads are a very good approximation to the directly measured ones (Fig. 3A, bottom) and that the unipolar leads are a maximum when the dipole is directed toward the corresponding limb.

**Task 4. ECG Measurement with a Simple Handheld ECG Device**

As a final task, the students are asked to measure their own electrocardiograms with a simple, handheld, one-lead ECG device. The ECG signal is measured between the thumbs of both hands. In addition to a normal condition (Fig. 3B, top), the measurement is repeated after the students have made 10 push-ups (or squats), which allows them to observe the increased heart rate from the ECG reading. Finally, the ECG signal is also measured with interchanged positions of the thumbs on the electrodes (Fig. 3B, bottom). With the knowledge obtained from the ECG model, the students understand why the ECG signal with the interchanged positions of the thumbs is flipped upside down.

Using the ECG device, the students can also observe how the ECG depends on the electrical conductivity of the contact between the electrodes and the skin. For example, if dry tissue paper representing dry, hairy skin is placed between the electrode and the skin, no signal is recorded. On the contrary, if the tissue paper is soaked with saline (or other conductive liquid), the signal becomes normal. The quality of the observed ECG can be linked to the measurements of the electric potential in the ECG model with the same materials inserted between the voltmeter probe and the rubber foil (see task 2).

This final task allows the students to link the knowledge obtained from the simple ECG model to a real ECG signal, and the ECG ceases to be a “black box” that measures abstract signals from the body. Importantly, this task often sparks further discussion about electrocardiography. For example, the students are ready to understand that the sinusoidal ECG signal measured in task 3 is a consequence of a constant magnitude of the rotating heart dipole that was used in the model ECG. In contrast, the changing magnitude of the real heart dipole leads to the peaks of different heights in a normal ECG reading.

**DISCUSSION**

The complex electrical activity of the heart induces measurable changes of the electric potential throughout the body. In a typical diagnostic setting, the ECG device is connected to 10 electrodes attached to specific parts of the body and measures the time course of 12 standard voltage differences, the so-called standard leads. These two-dimensional graphs are the only information clinicians have when they deduce the threedimensional behavior of the depolarization and repolarization waves in the heart. This is not an easy task, and therefore a good visual representation of the processes involved in the generation of an electrocardiogram is important. Although a basic understanding of ECG is necessary for all physicians and other personnel involved in medical care, it is also becoming more interesting for the general public, because of the increasing availability of personal ECG devices that allow online self-observation of one’s own ECG signal [e.g., Apple Watch (6)].

Therefore, a simple ECG model that enables the measurement and visualization of the equipotential lines around the electric dipole is presented. In our department, this hands-on experiment has been used for more than two decades for teaching medical students the basic principles of electrocardiography at a preclinical level. This approach proved to help the students learn the connection between the ECG signal, the measurement of the voltage on the limbs, the electric potential in the body, and the orientation of the heart dipole. In our view, the understanding and visualization of the equipotential lines in the body are the basis for understanding the ECG signal.

On a side note, there are two options for introducing the concept of the heart dipole to medical students. The approach used in many physics courses is based on a description of an electrostatic dipole in a nonconductive medium (4). The other option is to skip the electrostatics and start the description with a current dipole in a conductive medium (5). Although the first approach makes a quantitative description of the equipotential lines easier (the equations follow from the basic electrostatic concepts such as Coulomb’s law), the second one is closer to the actual electric dipole of the heart. It should be noted that the predicted shapes of the equipotential lines are essentially the same with both approaches (5). Thus, the choice of which approach to take can depend largely on the student’s background: the students familiar with electrostatics might find the analogy with the electrostatic dipole valuable, but those without a prior background in electrostatics can acquire the dipole concept directly through the current sources and sinks in the heart muscle cells.

To make the exercise more practice oriented and thus more stimulating and interesting for the medical students, they can also measure their own ECG with a handheld instant-check ECG device. At that point the students have already acquired a basic understanding of the ECG signal and are keen to compare a normal ECG signal to one obtained after some physical exercises. The prediction and measurement of the ECG signal with the interchanged thumbs on the electrodes serves as the last check of
whether the students have understood the principles of electrocardiography. Furthermore, the students can also easily see the importance of an appropriate contact between the electrodes and the patient’s skin by measuring the changes of their ECG with different materials inserted between the thumbs and the electrodes. In our experience, the hands-on experiment often triggers further discussion about electrocardiography.

In conclusion, our experience with the ECG exercise has been very positive. Students at a preclinical level can easily carry out all the tasks within one 90-min laboratory class, and the discussion after the class shows that the combination of a hands-on experiment on the ECG model and a real handheld ECG device is a valuable tool to link the basic science with clinical diagnostics.

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**DISCLOSURES**

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