A simple device to illustrate the Einthoven triangle

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The fundamental electrocardiographical concepts that Willem Einthoven developed more than a century ago are necessary for a full understanding of the heart’s electrical activity. This is the inspiration for the laboratory we have developed. We built a device that models an ECG, with three voltimeters for the three leads and a battery as the heart dipole electrically connected by a low-concentration saline solution, which mimics the electrical conductivity of our own bodies. Traditional ECG laboratories have had students take the lead measurements and then determine the dipole position of the heart; our developed laboratory allows students to manually change the position of the dipole and thus predict the measurements that will result in the three leads depending on the position, which is a new method of educating about the ECG. This laboratory emphasizes several objectives that students will ultimately learn: how to determine the orientation of the dipole vector from the voltages of the leads, Einthoven’s law (that lead I + lead III = lead II), and the requirements for the law to hold true in a system. The laboratory also explores a number of electrocardiography concepts that have traditionally been difficult to understand: for instance, that minimal and maximal measurements in certain leads depend on a specific position of the dipole and what positions those are or how the shape of the actual loop the three leads create affects the readings.

General Description

The new demonstration device consists fundamentally of a rectangular tray with an attached headboard as well as an acrylic board with an Einthoven triangle diagram that has an inscribed circle. The tray has four small pieces of wood cemented to the inside edges to support an acrylic board about half the distance from the bottom. The acrylic board has 1 AgCl electrode inserted into each vertex of the triangle, 1 electrode in the center of the triangle, and 12 electrodes evenly distributed along the circle. The attached headboard has three voltmeters to record the voltages in the three leads and a battery to simulate the heart’s electrical vector. Figure 1 shows the entire device.

This device was based on a demonstration offered to medical students by the Department of Physiology (University of California, San Francisco, CA) when J. H. Widdicombe worked there in the 1980s and 1990s.

Objectives

1. Students should learn how to determine the direction of the dipole from the voltages in the leads.
2. Students should learn Einthoven’s law: that lead I + lead III = lead II; thus, the deflection in one lead can be predicted from the deflections in the other two.
3. Students should learn that the relationship still holds true even in triangles that are not equilateral.
4. Students should learn that for Einthoven’s law to hold true, the loop created by the dipole leads cannot be open; the loop can be of any shape, but it must be closed.

Class

Each class of ~30 students is divided into 6 groups with 5 students per group, and every group performs the laboratory with 1 device. Through a guided process, every group has the chance to independently rediscover the aforementioned principles.

Laboratory

The laboratory class starts with students taking their own ECG. Based on these recordings, they identify the waveforms and calculate their heart frequencies and main cardiac vector. Next, they move to our device.

Laboratory Setup

To use this device, students place the acrylic board with the Einthoven triangle diagram into the box, on top of the supporting blocks. The alligator clips for each voltmeter are connected to the electrodes on the vertices of the triangle, representing the leads of the ECG machine. The space in the box below the acrylic board is filled with a 0.5 mM saline (NaCl) solution so
Students fill the bottom of the box with the 0.5 mM saline solution, electrically connecting all the electrodes (the low concentration of saline is intended to delay the polarization of the electrodes). It is important to note that this saline solution is what mimics the conductivity of the human body in an ECG recording and provides the environment similar to the electrical signal of the heart that is recorded at the surface of the body by way of volume conduction. Students wait for the values on the voltmeters to stabilize and then record the readings. This first recording provides the basis for how to operate the machine.

**Laboratory Procedures**

Now that the devices are set up and the students know how to operate them, they can begin observing particular orientations of the electrical vector.

**Minimal reading.** Students attach the positive terminal of the battery to the 30° point on the circle, which is in a perpendicular orientation to lead III. They discover that this orientation gives lead III a minimal reading, ideally 0 mV, whereas the values of lead I and lead II have deflections of the same magnitude but opposite signs. They repeat this operation for the other leads by placing the positive terminal of the battery to the 150° point (perpendicular to lead II) and the 270° point (perpendicular to lead I) on the circle. Students record the voltmeter values for each orientation, including the sign. They conclude that the minimal deflection in any lead is obtained when the dipole is perpendicular to that lead.

**Maximum reading.** The next orientation can be observed by placing the positive terminal of the battery to the 120° point on the circle. The electrical vector is now parallel to lead III and gives a maximum reading of lead III. Students repeat the measurements at positions of 60 and 0°, when the "cardiac vector" is parallel to leads II and I, respectively. They conclude that the maximum deflection in any lead is obtained when the dipole is parallel to the lead.

**Verifying Einthoven’s law.** Students place the battery connectors on the remaining orientations around the circle and record the voltage values in each lead for every position. Using all the collected data, students are asked to determine the unifying relationship connecting the recordings in each lead; ultimately, they (re)discover the following formula: lead I + lead III = lead II.

**Verifying Einthoven’s law despite loop shape.** Students can then disprove the common misinterpretation that the Einthoven triangle must be equilateral. They move the positive terminals of lead II and lead III to the 120° point on the circle, so that the triangle of the leads is not equilateral (Fig. 3). By placing the battery connectors as they normally would on any point on the circle, the students verify that the formula still holds true and that a nonequilateral triangle can be an Einthoven triangle.

**Disproving Einthoven’s law for open loops.** Students can then check if the formula still holds true in open loops. They keep the positive terminal of lead II at the 120° point and move the positive terminal of lead III to the 60° point, so that the triangle is open (Fig. 4A). They can verify that for any orientation of the battery vector, with this open loop, lead I + lead III does not equal lead II. Thus, they conclude that an Einthoven triangle must be closed.
Einthoven quadrilateral. Students can construct an “Einthoven quadrilateral” by closing the loop with an external voltmeter, referred to as lead IV. Before students begin, they are asked to hypothesize what the value of the voltage will be in lead IV. They attach the negative terminal of lead IV to the 120° point and the positive terminal to the 60° point, creating a closed trapezoid shape with the four leads (Fig. 4B). Students will realize from the vector positions that a new formula arises: lead I + lead III = lead II + lead IV. This new position substantiates the point that the Einthoven triangle is really an Einthoven loop: so long as the loop is closed, all of the readings must “balance.” A triangle is just the most practical shape, as it uses the least number of sides/leads.

Einthoven’s law and QRS progression. Students can use their knowledge of the conduction pathway and normal ECG to sequentially move the battery lead through a series of positions that follow the QRS progression. This allows students to appreciate the transitions between the Q, R, and S waves. This also helps to solidify the more abstract Einthoven triangle principles into the dynamic physiological context of the ECG.

For final verification, using the previously measured ECG, students can use the formula lead I + lead III = lead II to calculate the value of lead III from the values of lead I and lead II.

Student Evaluation

This device has been used in a laboratory for the HPH400 Human Physiology course, and the laboratory received an average student analysis rating of 5.98/7.00, using a standard student course evaluation grading scale, with a score of 1 meaning “poor” and a score of 7 meaning “excellent.” This score of 5.98 is very good; in fact, compared with congruent courses taught in the previous years but without the device we built, this rating is 0.92 points, almost a full point, higher than past ratings. This shows the effectiveness that the device has in conveying ordinarily difficult ideas.

The process of self-education that this device and its laboratory presents constitutes an improvement on the conventional teaching approach; the general consensus from students regarding the laboratory was “[v]ery helpful in lab” as well as “[v]ery good at explaining the concepts in a clear and concise manner,” as directly quoted from the student level-1 evaluation forms.

Discussion

Customarily, the ECG laboratory consists of students taking their own recordings, identifying the waveforms, and measuring heart frequency, with little room for experimentation; our machine provides an active learning approach by allowing students to
interact with this abstract representation of the heart’s electrical activity. Students can change the vector position, measure the values of the leads in different orientations, and finally reach the same conclusions that Einthoven determined 100 yr ago. Thus, these concepts are not memorized out of a textbook but are rather synthesized through rediscovery. Additional reading (APPENDIX C), combined with our apparatus, provides an active learning experience and ensures that the students receive a well-rounded education on Einthoven’s principles.

APPENDIX A: MATERIALS AND HOW TO BUILD THE DEVICE

Materials

The device was built from a 10.5 × 13 × 2-in. single-tier particleboard letter tray, with a 9 × 6-in. headboard of the same material. Four support particleboard pieces, 3/4-in. high, are placed along the inside of the box, with their upper surfaces 3/4 of an inch from the bottom. A 10 × 12-in. acrylic board, which has the illustration of the Einthoven triangle, is laid into the box, on top of the supports. It is an equilateral triangle with an inscribed circle. Holes are drilled in the vertices and center of the triangle as well as every 30° along the circumference of the circle. Silver electrodes, which have been chlorided by an immersion in sodium hypochlorite, are glued into and through each of these holes to form the Einthoven triangle and its inscribed circle, shown in Fig. 1. A template for the Einthoven triangle diagram is shown in Fig. 5. Along the circumference, each electrode is labeled by its angle measured counterclockwise from the 0° electrode.

The headboard contains three analog voltmeters placed horizontally, as they connect to and display the voltage of each lead. In the center of the headboard is the battery, which represents the electrical dipole of the heart. Finally, there is a switch to turn on/off the machine. Figure 6 shows the headboard.

Table 1 shows a complete list of the materials necessary to build this device.

How to Build the Device

Start with the headboard. Using the 9 × 6-in. piece, cut three rectangular holes (2 × 1 in.) evenly spaced and horizontally across the board. Within each hole, attach one voltmeter such that the screens of all three voltmeters are visible through one face of the headboard. The back of the headboard must now be wired so that the three voltmeters are connected to their respective 9-V batteries. Drill a hole into the lower left of the back of the headboard, closer to the side, and screw in the power switch. The voltmeters now must be attached to the main power switch. Finally, drill a hole in the center of the D battery holder.
Finally, place the acrylic board on top of the supports inside the box. Figure 1 shows the finished product with the connected leads and a sample recording.

APPENDIX B: A BRIEF HISTORY OF EINTHOVEN AND THE ECG MACHINE

The invention of the electrocardiograph at the beginning of the 20th century constituted a major advance in the diagnosis of heart disease (4). Earlier attempts made by Augustus Waller to measure the electrical activity of the heart by means of a mercury capillary electrometer were radically changed by Willem Einthoven (9). When Einthoven introduced his machine in 1902, it was a technological marvel, composed of many of the most recent technical advances. Its most delicate component, the string galvanometer, was the most sensitive electrical measurement device of the time (2); the movements of the thin filament were recorded in a photographic plate that used a recently developed emulsion; the light source used was the brightest option available, the carbon arc (used in lighthouses at that time); the projecting microscope made by Zeiss had to be specially designed in Jena, Germany; and the lenses, due to the large magnification used, needed to have minimal chromatic aberration and required a new type of glass, invented in 1886. Twenty years before the electrocardiograph’s introduction, many of its components remained to be invented, and its conception was almost inconceivable (2).

In addition to using the latest technology, Einthoven constructed the machine with great ingenuity, as exemplified in the method used to create the string galvanometer’s filament. This thin cable was produced by shooting an arrow with its tail attached to a thread of molten glass. The resulting filament was only 3 μm thick, thus reducing the wire’s inertia and greatly increasing the galvanometer’s sensitivity, especially compared with that of the original 20-μm-thick metal wire developed by Clement Ader in 1897. Another example of Einthoven’s innovative mind was the use of telephone lines to transmit the electrical signals of a patient located a mile away to his laboratory in Leyden, The Netherlands (1), making him not only the father of electrocardiography but a pioneer of “telemedicine” as well.

The original apparatus in Leiden weighed 600 lb, mainly because of the enormous electromagnet, which required a continuous-flow water jacket to prevent it from overheating. It needed five people to operate and occupied two rooms. Despite the early predictions that “this device will not find any extensive use in the hospital” (9), Einthoven saw the potential clinical use of his device. He contacted a scientific instrument company in Munich, Germany (Edelmann), as well as the Cambridge Scientific Instrument (CSI) Company in London, United Kingdom, to manufacture his invention. Both companies produced the machine, but Edelmann refused to pay royalties under the claim that they had subst-
tially modified the design (4). During the next 20 yr, the electrocardiograph was developed and commercialized until machines that could be moved to a patient’s bedside were available in 1920. A few years later, electrocardiographs that could be carried instead of rolled around were produced by the CSI Company. Although portable, they consisted of two wooden cases weighing 50 lb each (8). In 1935, a lighter machine was manufactured contained within a single case and weighing only 25 lb. The appearance of these “portable” devices accelerated the spread of electrocardiography. Further developments in the area of physics and electronics led to the miniaturization of the components and a further reduction in the size of ECG machines, such as those in implantable cardioverter-defibrillators.

Einthoven laid down the basis of modern electrocardiography. He set the standard derivations, the names of the waveforms (5, 6), and the recording speed (25 mm/s) used by today’s clinicians. His vision and conviction that his new machine would be a powerful tool to understand the heart’s electrical activity set the stage for establishing electrocardiography as a field of practical value (7). The validity of the Einthoven triangle theory initially created some controversy among clinicians (3), and a variety of methods were used to validate Einthoven’s postulates (11), such as passing electricity through a human cadaver and comparing the measurements with theoretical predictions. Nowadays, Einthoven’s relationship is the first step in learning electrocardiography. The device presented here is an effective alternative to the traditional teaching method to demonstrate the key concepts of Einthoven’s discoveries.

APPENDIX C: SUGGESTED READINGS

The following are suggested readings for this laboratory:


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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

AUTHOR CONTRIBUTIONS

Author contributions: B.E.J., J.Z., and J.L.P. performed experiments; B.E.J. and J.L.P. prepared figures; B.E.J. and J.Z. drafted manuscript; B.E.J., H.W., J.H.W., J.Z., and J.L.P. edited and revised manuscript; B.E.J., H.W., J.H.W., and D.M.B. approved final version of manuscript; J.H.W. and J.L.P. conception and design of research.

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