ILLUMINATIONS

Electrify your class with a simple battery: battery demonstration of electrocardiogram vectors

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Lujan HL, Wellette-Hunsucker A, DiCarlo SE. Electrify your class with a simple battery: battery demonstration of electrocardiogram vectors. Adv Physiol Educ 44: 394–399, 2020; doi:10.1152/advan.00055.2020.—William Arthur Ward stated, “The mediocre teacher tells. The good teacher explains. The superior teacher demonstrates. The great teacher inspires.” Discovery experimentation is an inductive method that demonstrates and inspires by creating an interest in determining the underlying basis of a phenomenon. This experiential approach also fosters motivation and enhances learning. Starting with what the student knows augments this approach. By starting with what the student already knows, the student can consciously and explicitly link the subsequent new information with previous knowledge. Accordingly, we used a simple battery as an analogy for electrocardiogram vectors to introduce the theoretical physics of how the heart produces voltages that are detectable at the body surface. This extraordinarily complex physics was approached in a straightforward and inexpensive way while still providing an understanding of the fundamental concepts developed by Willem Einthoven in 1895. This simple analogy introduces basic and more complex concepts (in a simplified manner) related to the electrocardiogram and electrocardiogram vectors and addresses the lack of other simplified educational tools for understanding these concepts. Specifically, the familiarity with how a battery works assists in the understanding of how electrocardiogram vectors are recorded and interpreted.

Background.

We cannot teach people anything, we can only help them discover it within themselves. —Galileo Galilei (2)

Cardiac muscle, like nerve and skeletal muscle, is an excitable tissue that has a resting transmembrane potential approximately equal to −90 mV. These cells only contract if they are depolarized to threshold and form an action potential. Cardiac muscle cells are connected by gap junctions, which are located within the intercalated disks. The gap junctions are microscopic, low-resistance “bridges” of cytosol between cardiac muscle cells, through which ionic currents can flow. Because of these cytoplasmic connections, an action potential in one cell causes a depolarizing current to spread into neighboring cells, which initiates an action potential in those cells. In this way, an action potential spreads from cell to cell, through the whole heart. Cardiac muscle cells, therefore, behave electrically as if they were all one cell, a characteristic called functional syncytium (literally, “acts like same cell”). Thus each contraction is initiated by a coordinated cardiac action potential of all of the cardiac muscle cells in the atria (atrial systole), followed by a very brief pause, and then a coordinated action potential (and contraction) of all of the cardiac muscle cells in the ventricles (ventricular systole).

The electrocardiograph machine is simply a voltmeter that detects and makes a recording of the voltage fluctuations at the surface of the body that are caused by the passage of action potentials from cell-to-cell through the heart. The record of these voltage fluctuations (made by the electrocardiograph machine) is called an electrocardiogram (ECG).

The ECG readily detects the occurrence of atrial depolarization (the resulting voltage change is called a P-wave), ventricular depolarization (QRS voltage complex), and ventricular repolarization (T-wave). Each normal heartbeat thus creates a predictable sequence of P-QRS-T.

Measuring electrical activity. A separation of positive and negative charges, and thus an electrical potential difference, exists between the inside and outside of cells (i.e., a voltage
exists across cell membranes, called a transmembrane potential. Transmembrane potentials exist because the ionic concentrations of the cytoplasm inside the cell differ from those of the interstitium outside the cell, and because ions diffusing down concentration gradients across semipermeable membranes generate electrical gradients.

Again, the heart behaves as if the mass of muscle comprising the atria and the ventricles were single individual cells. Because there are tight electrical junctions between cells in the ventricles, if any area is depolarized, the wave of depolarization will spread throughout the mass of tissue without decrement until the entire mass is depolarized. Thus the heart can be viewed as a dipole, with the polarized part of the heart representing the positive pole and the depolarized part of the heart representing the negative pole.

Students are familiar with the fact that batteries also consist of a separation of positive and negative charges and thus an electrical potential difference exists between the negative terminal and the positive terminal of the battery (i.e., a voltage exists between the negative and positive terminals). Specifically, chemical reactions in a battery cause an accumulation of electrons at the negative terminal, which results in an electrical difference between the negative and positive terminals.

An accumulation of electrons at the negative terminal results in an unstable condition. That is, the electrons attempt to eliminate the difference in potential between the two terminals of the battery. Specifically, electrons repel each other and move to a place with fewer electrons. The only place for the electrons to go is to the positive terminal. This requires that the circuit becomes closed. Placing the battery into a bowl of saline connects the positive and negative terminals, much like connecting a wire between the positive and negative terminals (ends) of the battery (Figs. 1 and 2).

The heart is also in a “bowl of saline” in that the heart is surrounded by extracellular body fluid, which is essentially salt water. As a cardiac action potential spreads outward from the sinoatrial node across the atria, the atria form a dipole, and this creates voltage differences in the saltwater bath that can be detected by a sensitive voltmeter. Specifically, voltmeter (ECG) electrodes placed at the body surface can detect voltage differences in the body fluid that are created as a cardiac depolarization spreads through the atria and the ventricles.

The theoretical physics of how the heart produces voltages that are detectable at the body surface is extraordinarily complex. However, to help students develop an intuitive understanding of how electrocardiography works, we begin by placing a common flashlight battery into a bowl of saline. When a common flashlight battery is placed into a bowl of saline, positive ions begin to flow through the water from the positive end of the battery to the negative end. This ionic current creates voltage differences in the saline that can be detected by placing the electrodes of a common voltmeter into the saline. The battery, having excess positive charges at one end (the end labeled “+”) and excess negative charges at the other end (“−”), is a specific example of an electrical dipole (positive and negative charges separated by a distance) (Fig. 2). We used this fact to demonstrate ECG rules and principles of cardiac vectors.

Points of confusion. Before we discuss ECG rules and principles of cardiac vectors, we clarify two points of confusion. First, by convention, it is stated that electricity flows from the positive (+) terminal of a battery to the negative (−) terminal of the battery. This flow of electrical charge is called conventional current. However, when electricity was discovered, scientists did not know which way the electricity was flowing around circuits. At that time, they decided to say that electricity was a flow of positive charges from + to −. Then, in 1897, the electron was discovered, and the guess made in the early days of electricity was
wrong! Electricity in almost all conductors is really the flow of electrons (negative charge) from − to +. However, by the time the electron was discovered, the idea of electricity flowing from + to − (conventional current) was firmly established, and we should use conventional current when trying to understand how circuits work (positively charged particles flowing from + to −). Furthermore, by convention, the voltage phasor (or the electric field intensity) points to the positive pole. Thus the orientations of the batteries in Figs. 3–7 are projecting from − to + because the voltage phasor (and its direction) is used, by convention, for Einthoven’s triangle.

It is also important to note that the electrical analogy of the heart and the battery is not perfect. For example, the constituent materials and operation of the battery is markedly different compared with the anatomy and physiology of the heart. Specifically, the battery operates by chemical reactions that cause an accumulation of electrons at the negative terminal, which results in an electrical difference between the negative and positive terminals. Additionally, the battery may be depleted and recharged. In this respect, a DC power source in series with a voltage-controlled oscillator may be a more appropriate electrical analogy.

**ECG rules.** Before the demonstration, we discuss the following ECG rules (Fig. 3).

1. A wave of depolarization traveling perpendicular to an electrode axis, lead I in this and all examples, results in a bidirectional deflection equal positive and negative voltages (i.e., no net deflection).
2. A wave of depolarization traveling away from a positive electrode results in a negative deflection.
3. A wave of depolarization traveling parallel to and away from the positive electrode results in the maximum negative deflection.
4. A wave of depolarization traveling toward a positive electrode results in a positive deflection in the ECG trace.
5. A wave of depolarization traveling parallel to and toward a positive electrode results in the maximum positive deflection.

The mediocre teacher tells. The good teacher explains. The superior teacher demonstrates. The great teacher inspires.

William Arthur Ward (5)

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**Preparation of the model.** See Fig. 2.

1. Using a standard hot glue gun, glue electrodes from a standard voltmeter to the bottom of a plastic container.
2. Connect the electrodes to the simple voltmeter. The electrodes may also be connected to a standard data acquisition system (e.g., ADInstruments, PowerLab) to obtain a tracing of the responses.
3. Fill the plastic container with normal saline.
4. Place a positive (+) symbol on the right corner of the plastic container.
5. Place a negative (−) symbol on the left corner of the plastic container.
6. Place a battery, with the positive terminal pointing up, into the saline bath perpendicular to lead I.

**Demonstration.** Rotate the battery through positions 1–8 (Figs. 4–7). Record the voltage at each position and plot the results.

**RESULTS**

An ECG trace is formed by the direction of the electrical potential over time relative to the axis of the recording lead.

**Relative to lead I.** See Fig. 4.

- Before depolarization (0), the voltage recording is at baseline.
- The initial wave of depolarization, relative to lead I, is traveling away from the positive electrode (1) and thus results in a small, negative deflection. A wave of depolarization traveling away from a positive electrode results in a negative deflection.
- At 2, the wave of depolarization is still traveling away from the positive electrode but less parallel to lead I and more perpendicular to lead I; thus the ECG tracing is less negative. Specifically, the voltage recorded along lead I is less because the projection of the vector onto lead I is smaller. That is, the voltage recorded along a particular lead axis is obtained by taking a projection onto that axis of the vector representing the magnitude and direction of depolarization at that time (Fig. 5).
- As the wave of depolarization continues to rotate counterclockwise (3), it now travels toward the positive electrode and results in a small, positive deflection: small and positive because the vector is nearly perpendicular to lead I.
- At 4, the wave of depolarization travels a little more parallel to lead I and toward the positive electrode, resulting in a larger, positive deflection.
- At 5, the wave of depolarization travels more parallel to lead I and toward the positive electrode, resulting in the maximum positive deflection.
- At 6, the wave of depolarization still travels toward the positive electrode but no longer parallel to lead I; thus the ECG tracing is less positive.
- At 7, the wave of depolarization still travels toward the positive electrode but much less parallel to lead I; thus the ECG tracing is less positive.
- Finally, at 8, the ventricles are no longer polarized; thus the ECG tracing is at zero.

**Relative to lead II.** See Fig. 6.

- Before depolarization (0), the voltage recording is at baseline.
The initial wave of depolarization is traveling nearly perpendicular to lead II but is pointing slightly away from the positive electrode. A wave of depolarization traveling perpendicular to an electrode axis, lead II in this example, results in a biphasic deflection of equal positive and negative voltages (i.e., no net deflection). However, the slight deviation from perpendicular away from the positive electrode results in a very small, negative deflection.

At 2, the wave of depolarization is traveling toward the positive electrode. A wave of depolarization traveling toward a positive electrode results in a positive deflection in the ECG trace. However, the positive voltage recorded along lead II is small because the projection of the vector onto lead II is small (more perpendicular to lead II than parallel).

As the wave of depolarization continues to rotate counterclockwise (3), it continues to travel toward the positive electrode and results in a larger, positive deflection (more parallel to lead II than perpendicular).

At 4, the wave of depolarization travels parallel to lead II and toward the positive electrode, resulting in the largest, positive deflection. A wave of depolarization traveling parallel to and toward a positive electrode results in the maximum positive deflection.

At 5, the wave of depolarization travels less parallel to lead II and toward the positive electrode, resulting in a smaller, positive deflection.

At 6, the wave of depolarization is traveling perpendicular to lead II. A wave of depolarization traveling perpendicular to an electrode axis, lead II in this example, results in a biphasic deflection of equal positive and negative voltages (i.e., no net deflection).

At 7, the wave of depolarization is now traveling away from the positive electrode; thus the ECG tracing is negative.

Finally, at 8, the ventricles are no longer polarized; thus the ECG tracing is at zero.

Relative to lead III. See Fig. 7.

Before depolarization (0), the voltage recording is at baseline.

The initial wave of depolarization is traveling toward the positive electrode. A wave of depolarization traveling toward a positive electrode results in a positive deflection in the ECG trace. The positive voltage recorded along lead III...
is relatively large because the projection of the vector onto lead III is large (more parallel to lead III than perpendicular).

- At 2, the wave of depolarization is traveling parallel to lead III and toward the positive electrode. A wave of depolarization traveling parallel to and toward a positive electrode results in the maximum positive deflection.
- As the wave of depolarization continues to rotate counterclockwise (3), it continues to travel toward the positive electrode, but results in a less positive deflection (more perpendicular to lead III than parallel).
- At 4, the wave of depolarization travels nearly perpendicular to lead III and toward the positive electrode, resulting in a small, positive deflection.
- At 5, the wave of depolarization is traveling nearly perpendicular to lead III. A wave of depolarization traveling perpendicular to an electrode axis, lead III in this example,
results in a biphasic deflection of equal positive and negative voltages (i.e., no net deflection).

- At 6, the wave of depolarization is now traveling away from the positive electrode; thus the ECG tracing is negative.
- At 7, the wave of depolarization is nearly parallel to lead III and away from the positive electrode; thus the ECG tracing has the maximum negative deflection.
- Finally, at 8, the ventricles are no longer polarized; thus the ECG tracing is at zero.

Man cannot discover new oceans unless he has the courage to lose sight of the shore.

**DISCUSSION**

von Kolliker and Müller, in 1856, were the first to discover that the heart generated electricity (6). Thirty-one years later, in 1887, Augustus D. Waller measured the first human ECG using a capillary electrometer to record an “electrogram” of the heart (10, 11). Subsequently, Willem Einthoven, the Dutch physician and physiologist, advanced the string galvanometer, invented by Clément Ader (1), to obtain greater sensitivity and higher fidelity recordings of the electrical activity of the heart and, in 1908, published a description of the first clinically important ECG measuring system (7). Einthoven was awarded the Nobel Prize in Physiology or Medicine in 1924 “for the discovery of the mechanism of the electrocardiogram” and transforming this curious physiological phenomenon into an indispensable clinical tool. In doing so, Einthoven established the fundamental basis of modern electrocardiography, and his insights and concepts are among the first step in understanding the heart’s electrical activity and electrocardiography.

In this Illumination, we describe a simple, inexpensive device that models an ECG. Using a discovery approach and this simple, inexpensive device, students manually change the position of the dipole and predict the measurements. The students also explore basic electrical physics and electrocardiography concepts, rules, and laws that have traditionally been difficult to understand. The students also discover how to determine the orientation of the dipole vector from the voltages of the leads.

Starting with what the student knows enhances the discovery approach. By starting with what the student already knows, the student can consciously and explicitly link the subsequent new information with previous knowledge. In this way, existing concepts are identified, and new linkages are formed between concepts. A simple analogy provides a means to identify existing concepts and form linkages with new concepts. In this way, a transfer of understanding from the familiar to the new occurs.

Don’t be afraid to fail. Be afraid not to try.  
Michael Jordan (9)

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