Electrocardiography Instructor Notes

Swarthmore College Introductory Physics for the Life Sciences

Answers to thought questions embedded in laboratory

> The T wave is upright (positive voltage) rather than inverted (negative voltage) because the direction of the repolarization current is opposite to the direction of the depolarization current, but the repolarization wave also travels in the reverse pattern of the depolarization wave.[1] So, the two reversals cancel out, leaving the T wave positive as well as the majority of the QRS.

Experimental notes

> The quality of electrical contact with the sticky electrodes degrades as they age, increasing the contact resistance and decreasing the amplitude of the voltage. However, as long as the signal is still clean, this doesn't affect the ability to analyze the data.

> Attaching electrodes at the wrists rather than the elbows, and the ankles rather than the knees, has relatively little effect because the limbs basically function as equipotentials.

Analysis notes

> Students are instructed to compare the maximum amplitude of their measured dipole moment to a typical dipole moment of a polarized molecule. We do this because an important goal of our course is for students to reflect on the reasonableness of measured and calculated values. As it happens, the value obtained by doing this is many orders of magnitude larger than that of 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. Doing this gives students practice in thinking about the quantity of the dipole moment, including its units.

> However, the alert instructor (and possibly the very alert student, though we have never had such a student) may recognize that this comparison is not truly appropriate, because the heart's dipole moment actually originates in the flow of current; it is not a charge dipole. Consequently, the measured ECG voltages do not allow direct determination of a charge dipole moment, and thus this comparison is flawed.

> We include this flawed comparison because we feel the habits of mind involved are valuable and it is beyond the scope of the course to explain the shortcomings. Nevertheless, instructors who are uncomfortable with this part of the analysis are encouraged to omit it and the editable files for the laboratory are provided to facilitate adaptation.

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[1] Some complex and remarkable physiology that leads to this reversal. The most interior layer of cells closest to the open space inside the heart ("subendocardial cells") have a longer refractory period between depolarization and repolarization than do the cells at the outer surface ("epicardial cells"), due to different densities of voltage-gated Na^+, Ca^{2+}, and K^+ channels.

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Answers to some likely physiology questions

- Muscle cell depolarization precedes contraction, so the electrical activity of the heart is likewise precedes the corresponding contraction or relaxation of the heart muscle.
- More (heart-specific) detail about how depolarization relates to contraction: In cardiac muscle, membrane depolarization triggers the release of Ca^{2+} from an internal storage in the cell called the sarcoplasmic reticulum (SR), which then activates the contractile apparatus. When the muscle relaxes upon depolarization, the Ca^{2+} is returned to that internal store, so Ca^{2+} is repeatedly recycled. There are tiny amounts of Ca^{2+} compared to Na^+ and K^+, but it is important in managing the electrical process.
- The direction of the maximum dipole moment vector is observed to normally vary from roughly horizontal (toward the left shoulder) to roughly vertical (toward the feet). This variation arises from different amounts of space in the chest cavity; as the distance from the spine to the sternum (breastbone) varies, that leaves different amounts of room for the heart, and thus leads to different orientations. In general, a more narrow chest pushes the heart more leftward and rotates it more upward, leading to a more horizontal dipole moment vector. [Seriously obese patients also tend to show this. Patients with chronic lung disease often have their lungs chronically overinflated, meaning that the diaphragm is kept lower than normal, leaving more room for the heart to hang downward.]
- Skeletal muscles depolarize and repolarize much more rapidly in bursts with many contractions per second of individual muscle fibers. (The rate of such contractions determines the amount of force generated by the muscle.) This does produce a modest electrical signal on the surface of the body, so if the patient is not still during an electrocardiogram, there will be what looks like a drift of the baseline.
- The diaphragm muscle also generates a moderately large electrical signal. A clinical ECG system filters out the low-frequency variation in the signal that comes from diaphragm contraction during breathing.
- The overall refractory period of the ventricles, which ends up being several hundred milliseconds, is what sets the heart rate overall; the atria repolarize after about 30 ms, so in atrial fibrillation, when the electrical timing of atrial contraction gets desynchronthe atria can contract at a 300 Hz rate.
- A tiny fraction of the population are born with the condition “situs inversus” which is mirror reversal of their internal organs; then Lead I is reversed and Leads II and III are exchanged. An ECG on such a patient appears identical to one on which the leads have been connected backwards.

More detail about the depolarization wave than presented in the reading

- Propagation of the depolarization wave in the heart tissue is quite different in detail from the spread of a nerve signal down an axon, although the physical origins are similar. Specifically, the depolarization of each individual muscle cell is rapid compared to the time required for the activation to spread from cell to cell within the heart tissue. Consequently, the dominant contribution to the heart’s electric field comes from the

current traveling from cell to cell rather than within a single cell.
In preparing the reading, the authors judged that this additional complexity does not help the students understand the physical origins of the electrocardiogram, and have chosen to keep the physiological picture as simple as possible to help students focus on the physics. We add this detail here for instructors in case students ask more advanced questions (in our ten years of experience teaching this material, very few students do).

Historical note on the "vector electrocardiogram"

In the past, in some clinical settings, the heart's time-dependent electric vector, reconstructed from the individual lead measurements with analog electronics in a manner analogous to that used in this laboratory, was sometimes displayed in real time on an oscilloscope-like instrument. This was referred to as the "vector electrocardiogram;" the display of the set of lead recordings is correspondingly called the "scalar electrocardiogram." The vector and scalar displays are two alternative approaches to displaying the same information.
Clinicians have since abandoned the vector electrocardiogram in favor of the scalar for clinical diagnosis and use.