

The Electrocardiogram

The electrocardiogram (EKG or ECG) is a common diagnostic tool used to monitor heart activity. In this experiment you will study the Physics of the EKG.

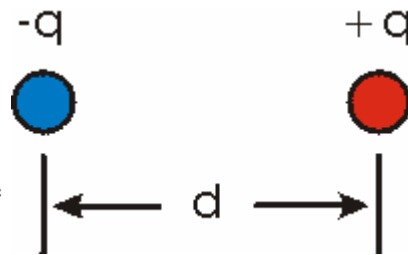
Prerequisites to this experiment are:

- An understanding of the electric potential at about the level of OAC high school Physics
- DC Circuits I
- Any experiment that uses an oscilloscope.

Background Information

The Electric Dipole

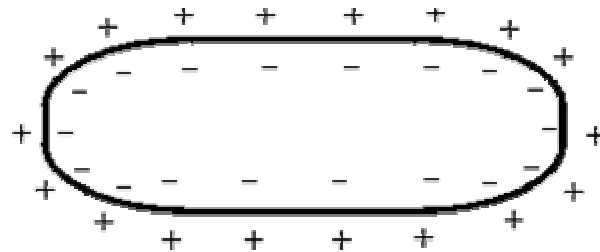
The electric dipole, as shown, consists of two equal and opposite charges, $+q$ and $-q$, separated by a distance d . The dipole moment p is defined as qd . We define the vector dipole moment \vec{p} as a vector whose magnitude is equal to the dipole moment and that points from the negative charge to the positive one.



(Caution: some people define the direction of the vector dipole moment to be from the positive to the negative charge.)

Muscle Cells

To the right we show a resting muscle cell. An active transport mechanism in the cell membrane maintains an excess of positive Na^{++} and Ca^{++} ions on the outside, and an excess of negative Cl^{-} ions inside. This means there is a potential difference across the membrane. In the heart, it is typically 70 mV for atrial cells and 90 mV for ventricular cells.



The positive and negative charge difference across each part of the membrane causes a dipole moment pointing across the membrane from the inside to the outside of the cell. But each these individual dipole moments are exactly cancelled by a dipole moment across the membrane on the other side of the cell. Thus the total dipole moment of the cell is zero.

By convention, we choose the potential of the interstitial fluid surrounding the cell to be zero, and then refer to all potentials relative to the potential of the fluid.

If a potential of about -70 mV is applied to the outside of the cell at, say, the left hand side, the membrane's active transport breaks down at that position of the cell, and the ions rush across the

membrane to achieve equilibrium values. These equilibrium values turn out to be a slight excess of positive ions inside the cell, giving a potential inside the cell of about +10 mV; you may have learned about the *Nernst equation* in a Chemistry class that gives these equilibrium values.

This potential difference at the left hand side of the cell causes the adjacent part of the cell membrane to similarly break down, which in turn causes its adjacent part to break down. Thus a wave of *depolarisation* sweeps down the cell from left to right with a velocity \vec{v} as shown.

Now the individual dipole moments across the cell membrane do not cancel each other out, and there is a net dipole moment of the cell pointing in the direction of the wave of depolarisation.

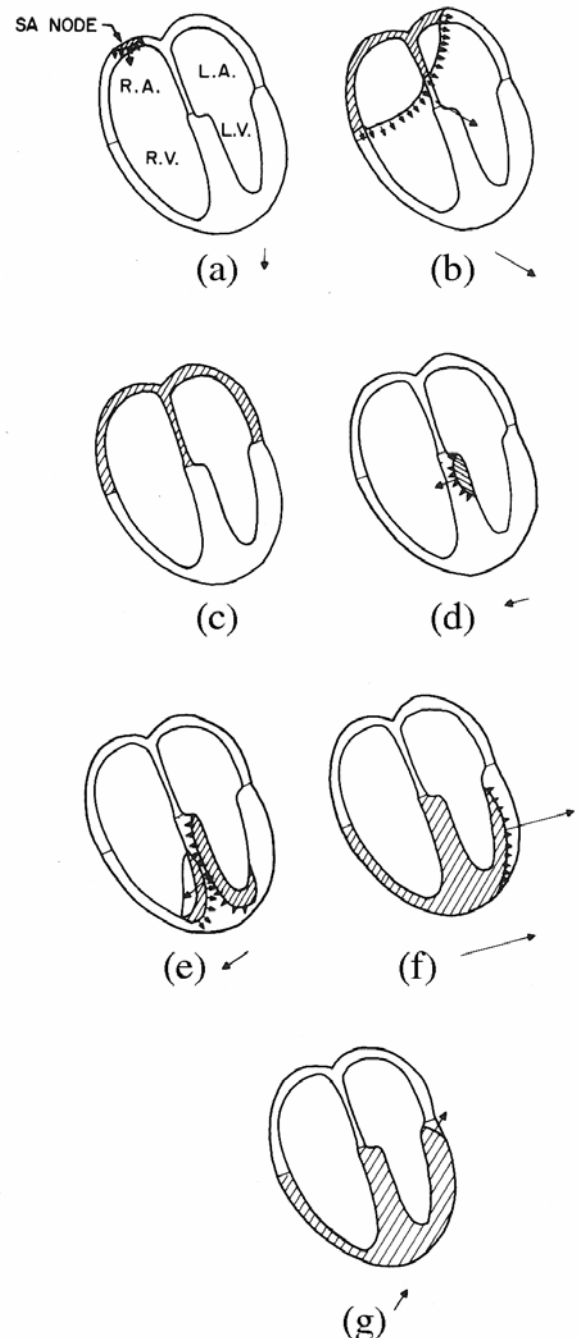
When completely depolarised, the positive Ca^{++} ion concentration inside the cell goes from about $5 \times 10^{-7} \text{ M}$ to $5 \times 10^{-6} \text{ M}$. The Ca^{++} catalyses the hydrolysis of ATP by *myosin* inside the cell, which then literally grabs the *actin* protein also inside the cell, causing the cell to contract. In this depolarised state there are individual dipole moments across the membrane, this time pointing from the outside to the inside, but just as for the resting muscle cell each dipole moment is cancelled by one on the other side of the cell so the total dipole moment is zero.

After about 250 ms the cell membrane begins to function again, pumping positive ions outside and negative ions inside the cell. Thus a wave of repolarisation follows the wave of depolarisation. Drawing a picture similar to the one of a depolarising cell above can convince you that there is a total dipole moment associated with the wave of repolarisation that points in the *opposite* direction to the velocity of the wave.

Muscle Tissues

In a muscle tissue, all the individual cells are aligned in the same direction. If a cell at, say, the left hand side of the tissue is stimulated by a negative potential, we have just described how a wave of depolarisation sweeps down the cell from left to right, followed by a wave of repolarisation. When the wave of depolarisation reaches the right hand side of the cell, the potential across that part of the membrane causes the next cell to the right to begin depolarising, and so on down the tissue. Thus a wave of depolarisation sweeps from left to right down the tissue, causing the muscle to contract. And associated with this depolarisation is a total dipole moment pointing in the direction of the wave. This is followed by a wave of repolarisation sweeping down the tissue from left to right, with an associated dipole moment pointing in the opposite direction to the wave.

The figure to the right shows the wave of depolarisation and muscle contraction sweeping over the heart. The



Sinoatrial node, labeled *SA* in the figure, is the natural pacemaker of the heart. It sends an electrical impulse that starts the wave of depolarisation sweeping through the right and left atria, labeled *R.A.* and *L.A.* respectively. This is shown in parts (a), (b) and (c) in the figure, with part (c) showing the atria completely depolarised. The atria and ventricles are not connected except at the point shown in part (d) of the figure where the depolarised atrial tissue triggers a wave of depolarisation that sweeps through the ventricles. The wave of repolarisation and muscle relaxation of the heart follows behind the polarisation wave in the same order.

The Experiment

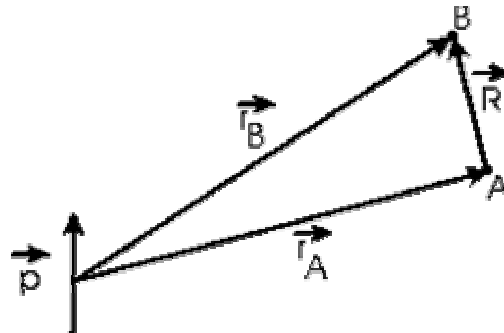
There are two investigations that you will do in this experiment:

1. Finding the potential difference between two points *A* and *B* due to an electrical dipole.
2. Measuring the dipole moment of your heart as it contracts and relaxes, and correlating that measurement with the physiology of the contraction discussed above.

1. The Potential of A Dipole

We shall be interested in the potential difference between two points *A* and *B* caused by an electric dipole \vec{p} as shown to the right. We shall call this potential difference ΔV , and it is equal to $V_B - V_A$. Both points are the same distance *r* away from the center of the dipole, and we assume that *r* is much larger than the distance *d* between the positive and negative charges of the dipole. We define the vector \vec{R} pointing from *A* to *B*; it is equal to $\vec{r}_B - \vec{r}_A$.

In what follows, we shall write the magnitude of \vec{R} as *R* and the magnitude of \vec{p} as *p*.



Setup

1. Place a sheet of the conductive paper printed side up on the supplied corkboard and fasten it at the four corners with the supplied pushpins.
2. Choose two of the crosses at the left hand side of the paper that are one cm apart and are vertically aligned, such as $(x, y) = (1, 9)$ and $(1, 10)$ cm. Press a metal pushpin through each position, but not all the way down
3. To the right is a picture of a *spade lug*. You are supplied two wires with a spade lug on at least one end. Place a spade lug from each wire under each of the metal pushpins from Step #2 and press the pushpin all the way down. Connect the other ends of the wires to the power supply.
4. Turn on the power supply and put about 25 V across the pins. You have now formed an electric dipole with the distance *d* between the charges equal to 1 cm. The magnitude of the dipole moment *p* is proportional to the applied voltage.
5. Confirm that 25 V exists across the pushpins by measuring it with the supplied voltmeter.



The Measurements

Choose some pair of points A and B on the far right side of the paper that:

1. Are vertically aligned, i.e. have the same value of x . Thus \vec{R} will be parallel to \vec{p} .
2. Are the same distance r away from the center of the dipole.
3. Do not touch any of the silver crosses or lines of the conducting paper.

Measure the potential difference by *lightly* pressing the leads from the voltmeter on to the conductive paper. Please be careful not to punch a hole in the paper.

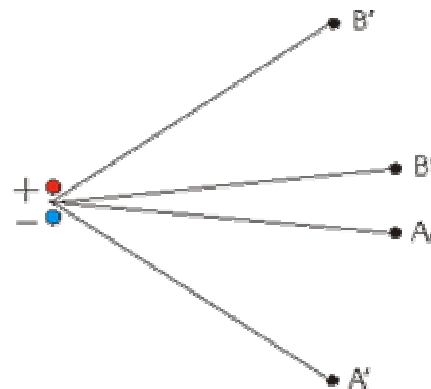
Measure how the potential difference between the two points A and B depends on the value of the voltage you are applying with the power supply, i.e. with the magnitude of the dipole moment.

Because the distance away from the dipole r is not really that large compared to the distance d between the charges of the dipole, there is a systematic error in applying your measurements to the case of being far from the dipole. Thus the errors in your measurements of r , R , or ΔV will not be useful in the following measurements, as this systematic error will be a little larger.

Return the applied voltage to the same approximate 25 V as before. Choose another pair of points on the right side of the paper satisfying the same three criteria as the previous pair of points, but with a different value of R . These two points should also be the same distance r away from the center of the dipole as the previous two points. Measure the potential difference.

Choose a few other points satisfying the same criteria as your previous one but for different values of R and measure the potential.

The figure to the right shows four points, A , B , A' , and B' that are all the same distance r away from the center of the dipole. The distance R' between A' and B' is larger than the distance R between A and B . But clearly A' and B' violate our assumption of being far away from the dipole more than A and B . Thus to find how ΔV depends on R will involve extrapolating your values to the one with the smallest value of R .



Now, answer the following question:

Assume, correctly, that for measurements that really are far away from a dipole $\Delta V \propto R^{n/2}$ where n is an integer, i.e. $\Delta V \propto R^{1/2}$ or $\Delta V \propto R$ or $\Delta V \propto R^{3/2}$ or ... What is n ?

Next we shall investigate how the potential difference depends on the relative orientation of \vec{p} and \vec{R} . Tape the two leads of the voltmeter together so that the distance between the two points R remains constant, and choose some point on the perpendicular bisector of the dipole moment and on the right side of the conducting paper. Keeping the midpoint of \vec{R} at this same point, pivot the

leads so that the angle θ between \vec{p} and \vec{R} varies. Do not have the probes touch the silver crosses or lines of the conducting paper. Take data for ΔV as a function of θ .

Note that here we are not only not very far away from the dipole, but we are letting the distance between the dipole and the two points A and B be slightly different. This is another nearly negligible systematic error.

Assume, correctly, that for measurements that really are far away from a dipole the potential difference $\Delta V \propto f(\theta)$ where $f(\theta)$ is a simple trigonometric function. What is the function?

You have now determined how the potential difference between the two points depends on:

- The magnitude of the dipole moment p .
- The distance R between the two points.
- The relative orientation of the dipole moment \vec{p} and the vector \vec{R} connecting the two points across which the potential difference is being measured.

Combine these three results into a simple vector relationship between \vec{p} and \vec{R} that is proportional to the potential difference ΔV .

Finally, as you should know, the potential of a point charge Q is given by:

$$V = \frac{1}{4\pi\epsilon_0} \frac{Q}{r}$$

Note the units of the term involving Q and r .

Assume, correctly, that for measurements that really are far away from a dipole the potential difference ΔV decreases as the distance r from the dipole increases, i.e.:

$$\Delta V \propto \frac{1}{4\pi\epsilon_0} \frac{1}{r^m}$$

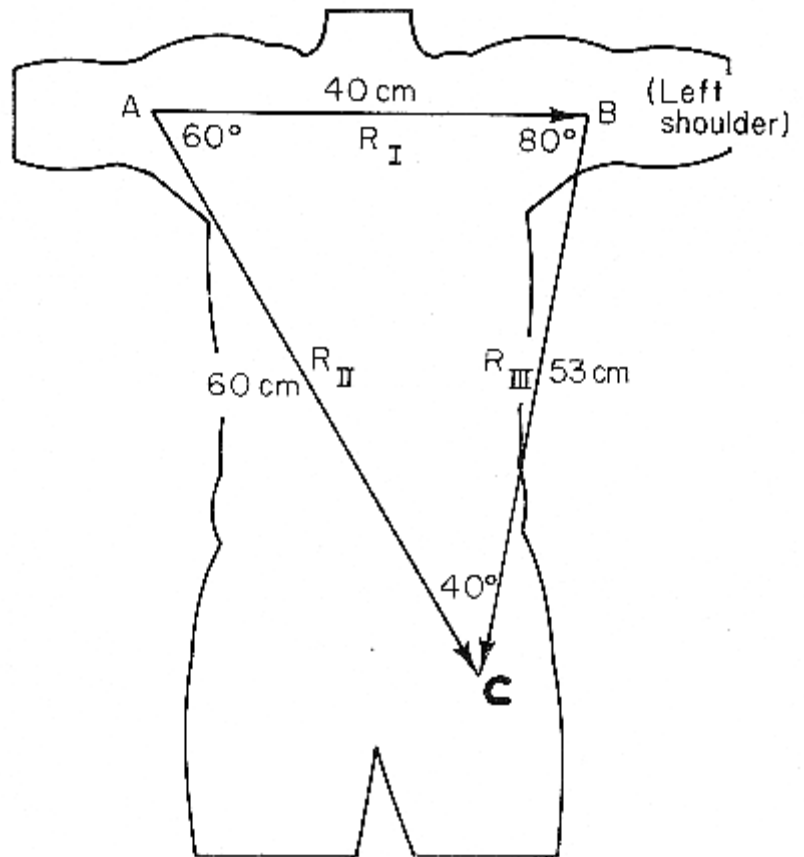
From the units of the equation for the potential of a point charge and your answer to the previous question, what is m ? Combine your answers to the questions of this part of the experiment into a single equation for ΔV .

2. The Electrocardiogram

In a diagnostic setting, one of the simplest EKG setups involves attaching leads to the patient's wrists and left ankle. The arms and left leg act as wires (resistance $\sim 150 \Omega$), so the effective points across which the potentials are measured are indicated by A , B and C in the figure to the right.

As you found in Part 1, the potential between A and B measures the component of the dipole moment in the direction of R_I , the potential between A and C the component parallel to R_{II} , and the potential between B and C the component parallel to R_{III} .

In this experiment you will be measuring the potential difference only between points A and B .



Setup

You will see two “handles” which later you will grasp. Connect them to the EKG amplifier, observing the polarity (red to red, black to black). Connect the EKG amplifier to the input of the oscilloscope labeled **CH 1**. Do not turn the amplifier on yet, but do turn on the oscilloscope.

After a few seconds, the screen of the oscilloscope will issue some diagnostics and tell you to press any button to continue. Press the button labeled **CH1 MENU**. You will see some choices on the right hand side of the scope screen, each associated with a physical button to its right. Set the following values: *Coupling = AC*, *BW Limit = On (20MHz)*, *Probe = 1X*, *Invert = Off*. (“AC coupling means any DC components of the input will be suppressed. “BW Limit” means bandwidth limit and when set as described suppresses all frequencies greater than 20 MHz.)

Press the button beside the *Volts/Div* item on the screen of the scope. Adjust the round knob labeled **Volts/Div** under the **CH1 Menu** button until the readout on the lower left hand corner of

the scope reads 500 mV ; this means that the vertical axis of your measurements will be 500 mV per cm on the scope face.

Next press the **HORIZONTAL MENU** button. Adjust the knob just under it until the readout on the center bottom of the screen reads 250ms . This means that the horizontal axis of your measurements will be 250 ms per cm on the scope face.

Now press the **TRIGGER MENU** button. Set the following values: *Edge, Slope = Rising, Source = CH1, Coupling = AC, Mode = AUTO*. This means that the sweep of the beam across the scope screen will be triggered automatically when the input voltage rises above a certain value.

Now turn on the EKG amplifier.

The Measurements

Grasp the “handles”. Note the labels on the handles (*L* for your left hand and *R* for your right hand). Some people need to slightly moisten their hands to get a good signal, and a very few people do not seem to produce measurable voltages at all. Also, since the voltages we are measuring are small, noise in the signal is a problem; sometimes it takes up to half a minute for the signal to settle down after you grasp the handles. Any body movement will have dramatic effects on the measurement, so you will need to stay still

Firmly grasp the handles connected to the EKG amplifier and observe the voltage being produced by your heart. You may need to press the button labeled **RUN/STOP** so the display at the center top of the screen reads *Scan*, not *Stop*.

You or your lab partner may need to adjust the trigger level with the round button labeled **LEVEL** just above the **TRIGGER MENU** button. The voltage level that triggers the next sweep is shown by the arrow on the right side of the screen. A good choice is to trigger on the large positive peak.

When you are getting fairly good signals, change the trigger mode to *Normal*. Now the scope stores each sweep of the beam and displays it until the next sweep is complete. You can stop the sweeping by pressing the **RUN/STOP** button, and then examine the trace at your leisure.

Adjust the *Volts/Div* to the minimum value that displays the entire signal.

You can reduce the noise by averaging over several heartbeats. Have your partner press the **ACQUIRE** button and select *Average* and a suitable number of averages from the menu. Finally, produce a hardcopy by pressing the **HARDCOPY** button.

At the end of the “Background Information” section we discussed the waves of contraction (depolarisation) and relaxation (repolarisation) that sweep through the heart muscles; in the previous sub-section we discussed how these waves generate net dipole moments in the tissues; in the first part of this experiment you showed how dipole moments generate voltages. Now correlate the voltages measured by the oscilloscope with the physiology of heart contractions. You will want to know that atrial repolarisation is masked by the ventricular depolarisation.

Different perfectly healthy individuals can sometimes show very different results in these measurements. You may wish to measure your lab partner and/or a few other people and compare the traces.

A library of EKGs of normal people and people with various forms of heart disease is at <http://homepages.enterprise.net/djenkins/ecghome.html>.

There is a further issue in interpreting your results. The “waves” of depolarisation and repolarisation follow each other, as stated, but they are not identical. In particular the wave of ventricular repolarisation tends to start at the bottom of the heart and propagate upwards; this is very different from the sequence of ventricular depolarisation associated with the contracting muscles. The ventricular repolarisation, then, moves largely in the vertical direction. But our apparatus measures the horizontal components. Thus small differences between individuals can be seen as the measured signal being positive, negative, oscillating, or even zero.

The major component of all the waves of depolarisation and repolarisation are similarly nearly vertical. This is why many diagnosticians pay little attention to the R_T measurements.

Appendix

Here we discuss the medical device called a *defibrillator*; the discussion is only for general interest.

We have seen in the Experiment that there are carefully controlled waves of contraction and relaxation that cause the heart to pump blood through the circulatory system. When the wave becomes un-synchronised, often due to damage to part of the muscle tissue, the pump ceases to work and the person is having a heart attack. This state of the heart is called *fibrillation*.

Muscle tissues that have a large current passed through them contract in a process called *tetanic contraction*, caused by forcing all the cell membranes to simultaneously depolarise. Thus an emergency technique for dealing with a heart attack uses a *defibrillator* to pass a large current through the heart, causing all the muscles to simultaneously contract. The hope is that when the muscles relax the wave of contraction and relaxation will be synchronised properly.

The defibrillator is basically a large capacitor ($C \sim 10 \mu\text{F}$) charged to about 6000 V. The wires connected to the capacitor lead to large paddles, which are placed across the chest and the capacitor is discharged.

When the defibrillator is discharged all the muscles in the chest are tetanised and the patient jerks on the table.

The peak current through the chest is about 60 A. This current passing through the chest causes significant heating of the tissues, so defibrillation can only be tried two or three times.

Apparatus

- One sheet of conductive paper, such as Pasco PK-9025.
- Corkboard for mounting the conductive paper.
- 6 pushpins, 2 of which must be metal.
- DC power supply capable of supplying 25V.
- 2 leads for the power supply, each with a spade lug on at least one end.
- Voltmeter with an 0.1 VDC scale or better.
- 2 leads for the voltmeter, each with a pointed probe.
- A few cms of masking tape.
- 1 clear plastic protractor.
- Tektronix TDS210 oscilloscope or equivalent.
- Printer for the oscilloscope.
- EKG amplifier and handles.

Acknowledgements

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Authors & Designers

This guide sheet was written by David M. Harrison in January, 2001. Parts of the *Electrocardiogram* part of the experiment are from the “Noise and Signals Around Us” experiment by Joe Vise, John Pitre and Tony Key, 2000. The EKG amplifier was designed by Brad MacInnis.

This guide sheet was last modified in February 2005.