Understanding Electrocardiography through Application of Electrostatics

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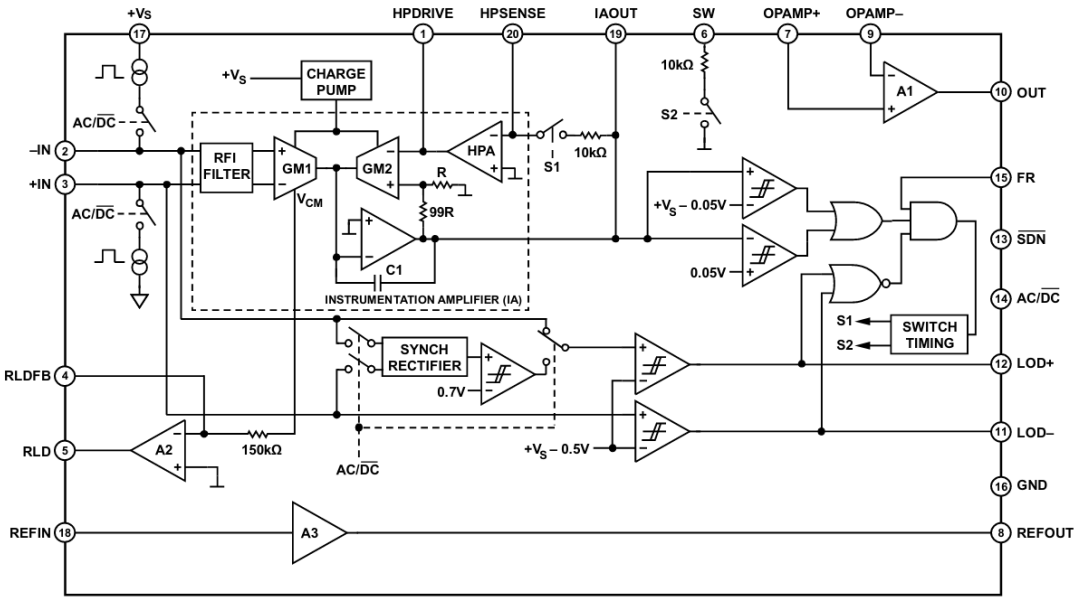
Introduction

Concepts in electricity and magnetism can be applied towards biological systems. In this lab we will explore how the myocardial cells act similar to charge distributions, and how heart cells and surrounding tissue can be modeled as electric dipoles. We will start by constructing an electrocardiogram (ECG) which measures electrical potential of the heart. We will then explore how the potential relates to the polarization of the heart and how we can understand the signal from the ECG with concepts from electricity and magnetism.

Procedure

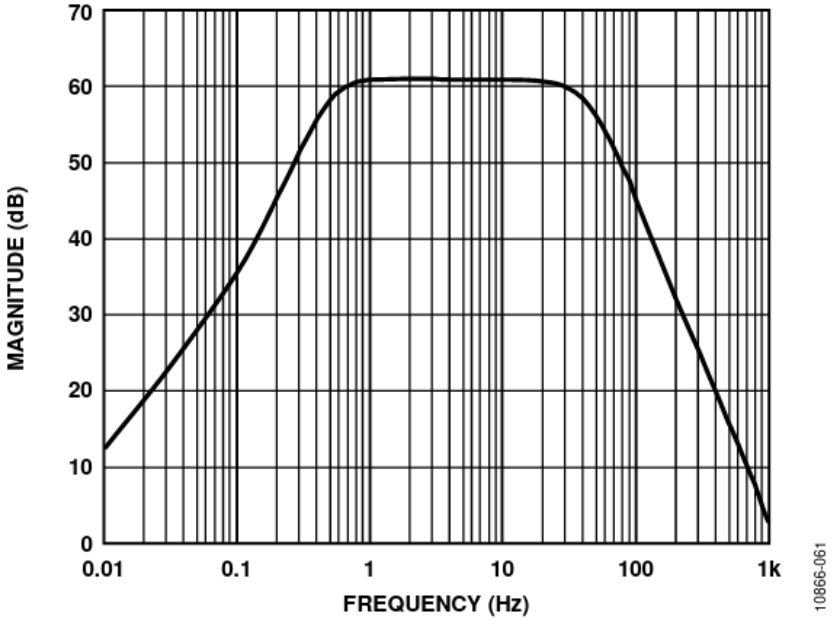
To begin this exploration we start by constructing an ECG. For the purposes of this lab I used an Arduino Uno microcontroller, a Sparkfun AD8232 heart rate monitor, and some Cleartrace ECG electrodes. The main component of this ECG is the AD8232 which contains the amplifier required to measure the potential across the leads as well as some useful filters to help improve the signal. The block schematic for the heart rate monitor is shown below in case one desires to construct the circuit from scratch.



[1]

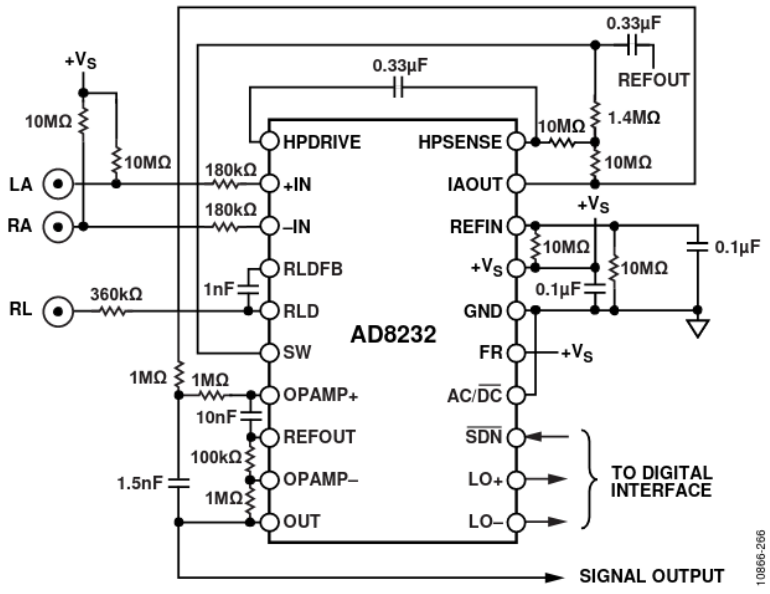
The AD8232 provides active configurable high pass and low pass filters to help improve the signal from the analog to digital converter and amplifier. If utilizing the breakout board from Sparkfun, these filters are already configured as a two-pole high

pass filter with a cutoff frequency of 0.5 Hz and a two-pole low pass filter with cutoff of 40 Hz as recommended by the manufacturer [1]. The frequency response of this setup is shown below.



[1]

To achieve this same setup without using the Sparkfun breakout board, Analog Devices provides the following schematic.



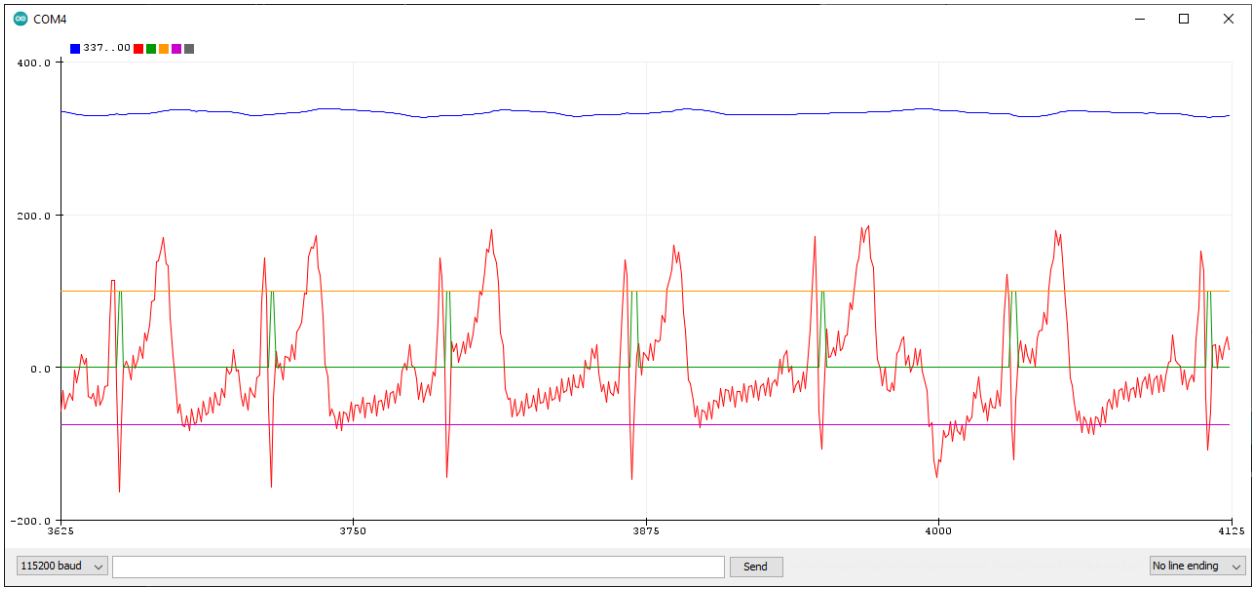
[1]

Figure 66. Circuit for ECG Waveform Monitoring

Once the heart rate monitor is properly configured the remaining procedure is relatively simple. The header pins from the breakout board of the AD8232 provide an easy way to connect the device to a microcontroller such as an Arduino Uno. The following table defines the proper connections.

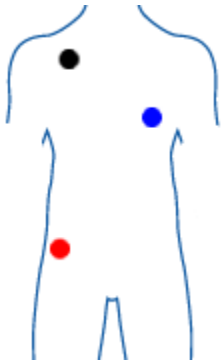
AD8232	**Arduino Uno**
GND	GND
3.3v	3.3v
OUTPUT	Analog Pin 0 (A0)
LO-	Digital Pin 11 (11)
LO+	Digital Pin 10 (10)

The purpose of the microcontroller is to provide a simple way to monitor the signal from the ECG. We can program the device to plot the ECG data and also do some simple signal processing. For this lab I elected to add an additional software lowpass filter to further smooth the signal and improve its consistency. I also applied a rudimentary beat detection algorithm to highlight the QRS complex. An example snippet from the serial output is shown below.



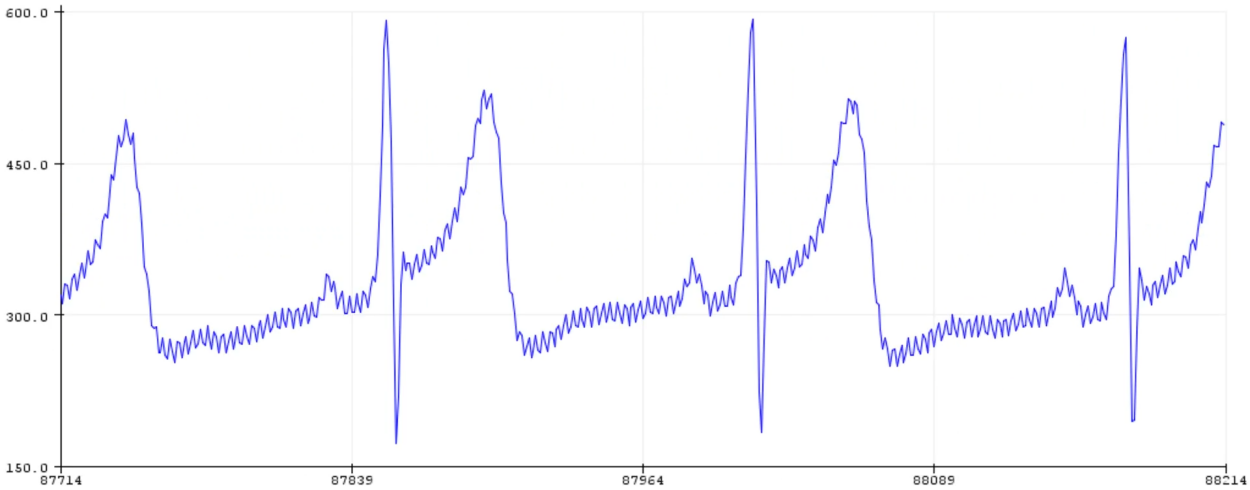
The red is the main ECG, the green highlights where the QRS complex is (used to detect a beat), and the orange and pink show the thresholds used for beat detection. The blue line is a running average of the ECG data used to center the ECG signal at zero. The code used, as well as video examples of the ECG data, can be found in my Github repository: https://github.com/evogelsa/ECG.

In order to collect data from the ECG, the leads must be attached to the body. There are multiple possible configurations that would work. The primary idea is to be able to detect the different polarization events from the heart by placing the leads according to Einthoven's Triangle [2]. I elected to go with the following configuration. I placed the black lead under the right clavicle, the blue just below and to the left of the heart, and the red grounding lead on my right hip bone. A diagram of this placement is shown below.



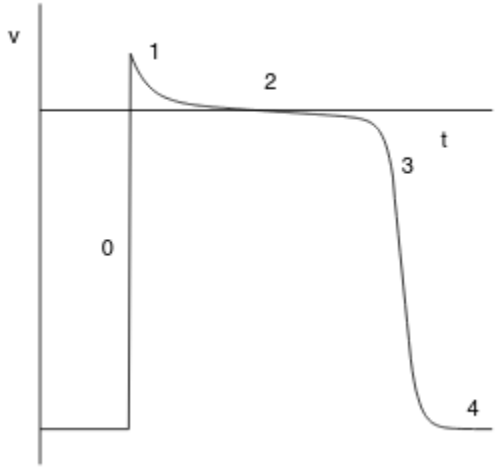
Results and Discussion

Now that we have successfully designed and experimented with an ECG, we can begin to discuss how the results can be understood using electricity and magnetism. First let us understand what the ECG measures. Below is a raw sample reading from the ECG which has been unmodified by software.

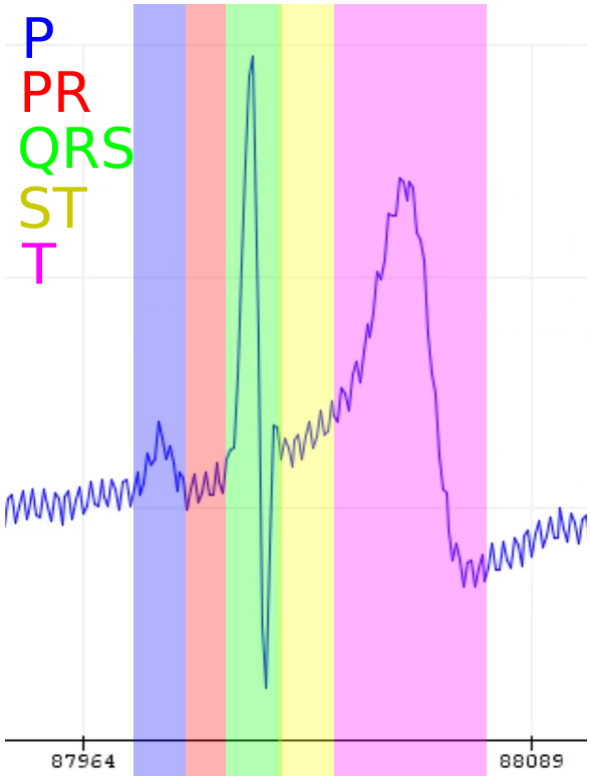


The blue line measures potential across the heart. The vertical axis represents the voltage potential and the horizontal axis represents the number of samples. Since I sampled the ECG data at 100 Hz the horizontal axis also directly corresponds with time.

Utilizing our knowledge of electrostatics, we can start to understand how these potential signals propagate and can be interpreted by the ECG. During a typical heartbeat, there are a few key events. First an inwards current causes a rapid depolarization of myocardial cells [3]. This depolarization will propagate throughout the heart, and the surrounding tissue, starting from the right atrium. This signal is what begins the contraction of the left and right atriums [3]. This wave of depolarization reaches the ventricles after the atriums, and it causes the ventricles to pump old blood into the lungs. After the heart has completely depolarized, a current efflux causes the heart to relax, and the myocardial cells start to repolarize [3]. A diagram from R. K. Hobbie shows the depolarization phase (0), the gradual decline (1, 2), and the repolarization phase (3) of a myocardial cell [3].



If we think of the myocardial cells and surrounding tissues as dipoles, we can understand how the ECG is able to detect these events. As current flows into the heart, the cells depolarize. This depolarization begins in the heart but it propagates into the surrounding tissues and causes a voltage potential spike. This potential is what is detected in the ECG. In fact we can highlight these exact events in our ECG signal. I have labeled the main events of an ECG signal according to [4].



In the P and PR sections, known as the PR interval [4], we observe the initial depolarization event. The next major event is the QRS complex which is caused by the ventricles beginning to pump, meaning that the atriums have completely depolarized and the depolarization has reached the ventricles [3, 4]. The ST phase corresponds to the slow decline/plateau in potential of the myocardial cells (phase 1 and 2 of the previous diagram) [3, 4]. Finally, the T wave shows when the repolarization event begins [3, 4]. Unlike the depolarization, repolarization is not so much a wave that propagates, but rather it is a local phenomenon that occurs in cells spontaneously after the initial depolarization has concluded [3].

Now that we understand how the signal is generated, we can look at the physics and math that allows us to actually measure these changes in potential. Because we can model these cells as dipoles, we can use our understanding of potential and its relation to distance from a dipole to create a model of the voltage. Starting with potential from a dipole we have:

$$v = \frac{\bar{p} \cdot \bar{r}}{4\pi\sigma_o r^3}$$ [3].

If we want to measure the difference in potential between two points then we can simply take the difference between two vectors representing the places we want to measure, r_1 and r_2, which giving us the following:

$$v = \frac{\bar{p} \cdot (\bar{r}_2 - \bar{r}_1)}{4\pi\sigma_o r^3} \quad [3].$$

When the myocardial cells are resting and before the depolarization begins, there is no dipole moment [3]. However, once the depolarization begins we are able to detect the rapid change in potential, especially once the depolarization reaches the ventricles. In a medical grade ECG there are many more than three leads, and each measures the potential differences between multiple points [3], but for the purposes of this lab, a simpler three lead ECG was used. This limits the amount of points that we can measure potential difference between to three, but it still provides a signal quality decent enough to distinguish the key events of the heart beat.

Conclusion

We have now explored how we can construct an ECG and interpret its signal. By applying our knowledge of electrostatics, we aid our understanding of biologic systems. We can model the myocardial cells as dipoles and, in doing so, we see how they act similar to charge distributions by their ability to polarize and depolarize in response to electrical currents generated in the body.

References

[1] Analog Devices, “Single-Lead, Heart Rate Monitor Front End,” AD8232 datasheet, Aug. 2012 [Revised Feb. 2013].

[2] Mary Bodreau Conover, *Understanding Electrocardiography*, 8th ed. Mosby, 2003. [E-book] Available: Google Books.

[3] R. K. Hobbie, “The Electrocardiogram as an Example of Electrostatics,” *American Journal of Physics*, Jun., pp. 824-831, 1973.

[4] Araz Rawshani, *Clinical ECG Interpretation*, ECGWaves, 2018, [E-book] Available: ecgwaves.com