Laboratory Project 1
The Electrocardiogram

DUE: 3/8/07

1 Introduction

The electrocardiogram (ECG) is a recording of body surface potentials generated by the electrical activity of the heart. The recording and interpretation of the ECG has a very long history, and is an important aspect of the clinical evaluation of an individual's cardiac status and overall health. In this laboratory project we will design a filter for conditioning the ECG signal and a monitoring system to detect abnormal rhythms.

2 The Electrocardiogram

2.1 ECG Beat Morphology

The normal heart beat begins as an electrical impulse generated in the sinoatrial node of the right atrium. From there, the electrical activity spreads as a wave over the atria and arrives at the atrioventricular node about 200 ms later. The atrioventricular node is the only electrical connection between the atria and ventricles. In approximately 100 ms, the wavefront emerges on the other side and rapidly spreads to all parts of the inner ventricular surface via the His-Purkinje system. The activation of the entire ventricular myocardium takes place in 80 ms.

The ECG waveform corresponding to a single heart beat consists of three temporally distinct wave shapes: the *P wave*, the *QRS complex*, and the *T wave*. The P wave corresponds to electrical excitation of the two atria, and is roughly 0.2 mV in amplitude. The QRS complex corresponds to electrical excitation of the two ventricles, and has a peaked shape approximately 1 mV in amplitude. The T wave corresponds to the repolarization of the ventricles. It varies greatly from person to person, but is usually 0.1–0.3 mV in amplitude and ends 300–400 ms after the beginning of the QRS complex. The region between the QRS complex and T wave, called the *ST segment*, is the quiescent period between ventricular depolarization and repolarization. Algorithms for detecting ECG beats invariably focus on the QRS complex because its short duration and high amplitude make it the most prominent feature.

The bandwidth of the ECG is not rigidly defined, although most of the clinically relevant energy falls between 0.05 and 50 Hz. However, important morphological features of the ECG may contain very little of the waveform's energy. Therefore, reproduction resulting in unchanged clinical interpretation may not necessarily be related to traditional engineering metrics such as preservation of the waveform energy.

2.2 Noise

It should be no surprise that noise can be a problem in ECG analysis. Fortunately, the signal-to-noise ratio is usually quite good in a person at rest. In an active person, however, there can be substantial low frequency (< 15 Hz) noise due to electrode motion, and high frequency (> 15 Hz) noise due to skeletal muscle activity. In addition, there is the possibility of noise at 60 Hz and its harmonics due to power-line noise.

2.3 Arrhythmias

All normal heartbeats begin as an electrical impulse in the sinoatrial node, and a sequence of normal heartbeats is referred to as a *normal sinus rhythm*. The term *arrhythmia* refers to an irregularity in the rhythm. Most arrhythmias are associated with electrical instability and, consequently, abnormal mechanical activity of the heart. Arrhythmias are typically categorized by the site of origin of the abnormal electrical activity. Although all normal heartbeats originate in the sinoatrial node, abnormal beats can originate in the atria, the ventricles, or the atrioventricular node.

Arrhythmias can consist of isolated abnormal beats, sequences of abnormal beats interspersed with normal beats, or exclusively abnormal beats. From a clinical perspective, the severity of the arrhythmia depends on the degree to which it interferes with the heart's ability to circulate oxygenated blood to itself and to the rest of the body. Isolated abnormal beats typically do not interfere with cardiac function, although they do indicate an underlying pathology in the cardiac tissue. Rhythms dominated by abnormal beats are often more problematic. Many of them can be treated with medication, while the most severe arrhythmias are fatal if not treated immediately.

Two especially dangerous arrhythmias are *ventricular flutter* and *ventricular fibrillation*. Ventricular flutter is produced by a focus of ventricular cells firing at a rate of 200–300/minute. In ventricular flutter the ventricles contract at such a high rate that there is not enough time for them to fill with blood, so there is effectively no cardiac output. Untreated ventricular flutter almost always leads to ventricular fibrillation, because the lack of blood supply causes many other foci in the ventricles to fire independently.

In ventricular fibrillation, many foci of ventricular cells fire, each at its own rate. Because there are so many foci firing at once, each one causes only a small area of ventricle to

depolarize, resulting in a chaotic twitching of the cardiac muscle and no cardiac output. Ventricular fibrillation is an emergency situation which requires treatment by electrical shock to restore the heart to a normal sinus rhythm.

2.4 Automated Arrhythmia Detection

Not surprisingly, much effort has been devoted to the development of automated arrhythmia detection systems for monitoring hospital patients. In such systems, the ECG signal is picked up by surface electrodes on the patient, amplified, lowpass filtered, and digitized before processing. Many signal processing techniques have been studied for reducing noise and identifying relevant features of digital ECG signals. The output of the system is a diagnosis of the rhythm which is typically recorded and/or displayed on the monitor. In addition, the detection of rhythms requiring immediate attention generally triggers an alarm. Although detection of ventricular flutter or ventricular fibrillation should obviously generate an alarm, it is important to minimize the false alarms produced by such systems. Experience has shown that automated arrhythmia detectors with high rates of false alarms are typically disabled or ignored by hospital staff.

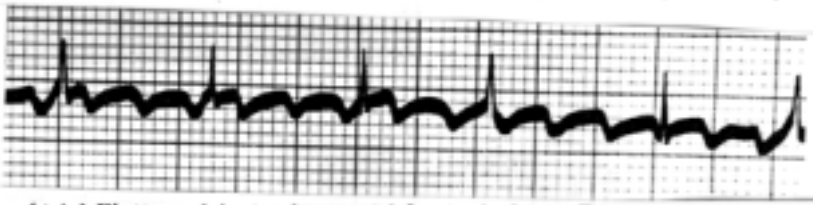
In the first part of this lab, we will design digital filters for signal conditioning. In the second part of this lab we will design, implement and test a system to distinguish ventricular flutter and ventricular fibrillation from normal sinus rhythms.

References

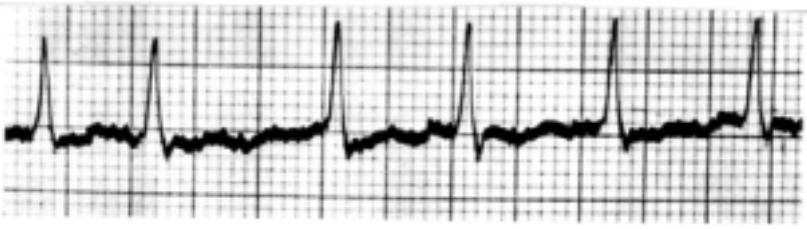
Dubin, D. *Rapid Interpretation of EKGs.* Cover Publishing Co., Tampa, 1973.

Ripley, K. and Murray, A., eds. *Introduction to Automated Arrhythmia Detection.* IEEE Computer Society Press, Los Alamitos, 1980.

From *Rapid Interpretation of EKGs* by D. Dubin.



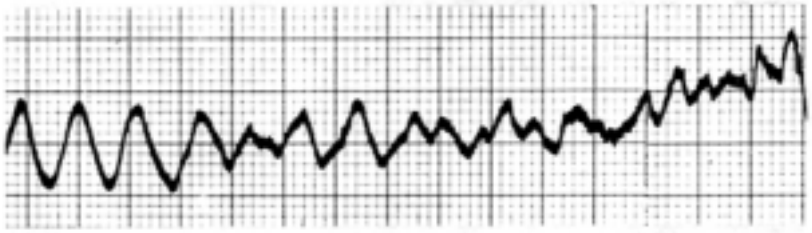
Atrial Flutter originates in an atrial ectopic focus. P waves occur in rapid succession and each is identical to the next.



Atrial Fibrillation is caused by *many* ectopic atrial foci firing at different rates causing a chaotic, irregular atrial rhythm.

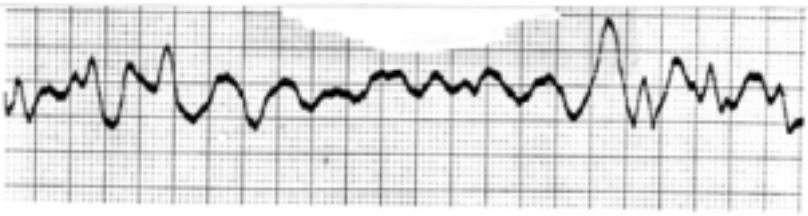
Ventricular Flutter is produced by a single ventricular ectopic focus firing at a rate of 200-300/min. Notice the smooth sine wave appearance.

Ventricular Flutter



... into Ventricular Fibrillation

True Ventricular Flutter almost invariably becomes Ventricular Fibrillation requiring cardio-pulmonary resuscitation and defibrillation.



Ventricular Fibrillation is created by stimuli from many ventricular ectopic foci causing a chaotic twitching of the ventricles.

3 Specific Instructions

3.1 Data Acquistion

The first data that you will process was recorded from a healthy volunteer. The signal was amplified with gain of 1000, filtered to include frequencies between 0.1 Hz and 100 Hz, then sampled at 250 Hz and quantized to 16 bits, with $V_{\max} = 5$V. During the first four minutes of the recording, the person was supine and quiet; during the last minute, the person periodically contracted the chest muscles so as to add some noise to the recording.

The data is stored in **/mit/6.555/data/ecg/normal.txt** and can be read into Matlab using the function **load**. The data matrix consists two columns, a vector of the sample times (in seconds) and a vector of the recorded ECG signal (in volts).

Question 1 *Draw a block diagram to illustrate how the data was acquired. Be sure to include important parameter values.*

Question 2 *If you examine the data, you will notice that the ECG data values have been rounded to the nearest millivolt. Is this a result of the 16-bit quantization, or was additional resolution lost after the quantization? Explain.*

Question 3 *Consider the analog filter used in the data acquisition. Why was the signal filtered prior to sampling? Why was a cutoff frequency of 100Hz used (instead of 125 Hz)?*

3.2 Week 1: Signal Conditioning/Noise Reduction

Find a typical 5–10 second segment of the clean data and examine the frequency content of the ECG segment (**pwelch**). Also select a 5–10 second segment of the noisy data and examine its frequency content. It may help to plot the spectral magnitude in decibel units. Note how the frequency content of the noisy signal differs from that of the clean signal.

Design a bandpass filter to condition the signal. The filter should remove baseline fluctuations and attenuate high-frequency noise. Select the cutoff frequencies by using the spectrum to determine the low and high frequency cutoffs that would preserve most of the energy in the signal. (Do not count the baseline-wander component as signal energy.) It is not necessary to design filters with extremely sharp transition bands; in particular, be flexible in choosing your bandpass filter's low-frequency cutoff. You may also want to experiment with the effect of varying the high-frequency cutoff.

Compute the frequency response of your bandpass filter. Plot the filter's impulse response and its frequency response (in decibels versus Hz).

Demonstrate its effectiveness by filtering both clean and noisy segments (5–10 seconds each) of the ECG data. How well does your filter remove the noise?

Hints:

- Be sure that all plot axes are labelled appropriately with both variable and units, for example: *time (sec)*
- Consider using **stem** instead of **plot** to display the impulse response of the filter.
- When looking at the frequency response of a filter, plot the magnitude in units of dB as a function of Hz. You might also want to plot the linear magnitude as a function of Hz.

Question 4 *Describe your bandpass filter. Including plots of your filter's impulse response and frequency response. Also include answers to the following questions: What were the desired specifications for the filter? How did you decide on those specifications? What filter design technique did you use? How well does your actual filter meet the desired specifications? Be sure to mention any difficulties in meeting the desired specifications as well as any tradeoffs you encountered in the design process. (Suggested length: 1–2 paragraphs.)*

Question 5 *Describe the effect of your bandpass filter on both the clean and noisy data. Include plots of the clean and noisy data in both the time and frequency domains before and after filtering and make relevant comparisons. (Suggested length: 1–3 paragraphs.)*

Question 6 *What are the limitations of this bandpass filtering approach? (If it were possible to implement an ideal bandpass filter with any desired specifications, would you expect to remove all of the noise?)*

3.3 Week 2: In-class Exercises and Interactive Tutor

Part of your grade for lab 1 will reflect your participation in this week's lab activities, particularly the web-based tutorial. Your grade **will not** depend on the correctness of your answers to the tutorial questions or on how many times you checked your answers before submitting them. Your grade **will** depend on whether or not you have submitted nontrivial responses to **all** of the tutorial questions. Please note that entering, checking and/or saving answers is not sufficient, you must **submit** your answers for each question page.

3.3.1 Accessing the 6.555 tutor

To register for a tutorial account, go to http://sicp.csail.mit.edu/hst-tutor/register.html and follow the directions there. You will receive your password via email within a few minutes.

Once you have received your password, you can access the interactive tutor via a link on the course homepage or directly at http://sicp.csail.mit.edu/hst-tutor. On the tutor home page, select 'Choose a tutorial'. Then select 'Spectral Analysis Tutorial'. (That's the only choice!)

3.3.2 Using the 6.555 tutor

Once you are in the spectral analysis tutorial, you will see a menu of resources on the left, and some introductory text followed by buttons for accessing the tutorial questions. Please read the introductory text and then proceed through the questions sequentially.

The page associated with each question contains one or more sub-questions. Buttons at the bottom of each question page give you the options to check, save, and submit your answers. These functions (check, save, and submit) apply only to the current question page, not to all questions in the tutorial. You may check your answers as many times as you wish, but *you may only submit your answers once for each question page*. After you have submitted your answers for a given question page, you can view the correct answers and an explanation, if available.

3.4 Week 3: Ventricular Arrhythmia Detection

In this portion of the lab you will design a system to detect ventricular arrhythmias. The abnormal ECG segments that we will use were taken from the MIT-Beth Israel Hospital Malignant Ventricular Arrhythmia Database. Each file contains a 5-minute data segment from a different patient. The signals were sampled at 250 Hz and quantized to 12 bits. The gain was set so that one quantization step equals 5 microvolts. In other words, the full range of quantized values, from -2048 to +2047, corresponds to -10.24 mV – $+10.235$ mV.

In order to design your system, you first need to determine criteria for distinguishing between the normal ECG and ventricular flutter/fibrillation. Select one or more of the data files listed below, read them into Matlab using the function **load**, and inspect the ECG signals. (The first two files on the list are probably the easiest to start with.) Each abnormal ECG segment contains some portion that is 'normal' for that patient. Select two or three pairs of data segments, where each pair includes a 'normal' rhythm for that patient and a segment where the ventricular arrhythmia occurs. Analyze the frequency content of all the segments (**pwelch**), and make comparisons between the normal and arrhythmic segments. Use your observations to propose a metric to distinguish ventricular arrhythmias from normal rhythms.

/mit/6.555/data/ecg/n_422.mat - episode of ventricular fibrillation
/mit/6.555/data/ecg/n_424.mat - episode of ventricular fibrillation
/mit/6.555/data/ecg/n_426.mat - ventricular fibrillation and low frequency noise
/mit/6.555/data/ecg/n_429.mat - ventricular flutter (2 episodes) and ventricular tachycardia
/mit/6.555/data/ecg/n_430.mat - ventricular flutter and ventricular fibrillation

/mit/6.555/data/ecg/n_421.mat - normal sinus rhythm with noise
/mit/6.555/data/ecg/n_423.mat - atrial fibrillation and noise

Question 7 *Explain your choice of parameters (window length, window shape, and FFT length) used to analyze the spectrum. What is the effective frequency resolution (in Hz) of the spectral analysis that you performed? Be sure to state the name of the Matlab function that you used and show how you computed the effective frequency resolution.*

Question 8 *How do the ventricular arrhythmia segments differ from the normal segments in both the time and frequency domains? (Include relevant plots.)*

Based on your metric, design a system to continuously monitor an ECG signal and detect ventricular arrhythmias.[1] Then test your detector on at least *two* of the first five data files listed above. If you have the time and inclination, try running your system on some of the other data files. In particular, the last two files give you a chance to see if your system generates false alarms when there is plenty of noise, but no ventricular arrhythmia.

Question 9 *Describe your approach to distinguishing ventricular arrhythmias from normal rhythms. Include a block diagram or flowchart of your system if appropriate. Please include the Matlab code for your ventricular arrhythmia detector as an appendix to your lab report. (Suggested length: 2–4 paragraphs)*

Evaluate the performance of your detector. Note that arrhythmia detection is a real-world problem which has not yet been completely solved. The goal of this lab is to explore a possible solution to the problem, *not* to develop a detector which works perfectly under all conditions. In order to evaluate the performance of your detector, you must compare the output of your system to the 'right' answer. In the case of automated analysis of ECG signals, the 'gold standard' is provided by the ECG classification performed by human experts. Although you may not be an expert yet, you can start by looking at the waveform in the time domain, identifying major transitions in the data record, and trying to identify intervals of normal rhythm and intervals of ventricular arrhythmias using your knowledge of ECG signals. In addition, the files /mit/6.555/data/ecg/atr_nXXX.txt provide expert classification (performed by a cardiologist) of the ECG signals in the corresponding data files.

Question 10 *How well does your detector perform? Include plots and/or other figures and tables to present the output of your system compared with the expert classification. Does your detector produce false alarms, missed detections, or both? Under what conditions is your detector more prone to errors? (Suggested length: 2–4 paragraphs)*

[1] A *very* general framework is provided in the file **/mit/6.555/matlab/ecg/va_detect.m**. Feel free to copy this file to your directory and use it as a framework for your system.

Question 11 *If you had much more time to work on this problem, how would you attempt to improve your detector? (Suggested length: one paragraph)*

Question 12 *What is the most important thing that you learned from this lab exercise? (Suggested length: one sentence)*

Question 13 *What did you like/dislike the most about this lab exercise? (Suggested length: one sentence)*