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HST.582J / 6.555J / 16.456J Biomedical Signal and Image Processing
Spring 2007

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HST-582J/6.555J/16.456J-Biomedical Signal and Image Processing-Spring 2008

Laboratory Project 1 The Electrocardiogram

DUE: 3/6/08

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 (SA) node of the right atrium. From there, the electrical activity spreads as a wave over the atria (at speed of about 0.5 m/s) and arrives at the atrioventricular (AV) node about 120 ms later. Under normal circumstances, the AV node is the only electrical connection between the atria and ventricles. Furthermore, conduction speed through the AV nodes is markedly slower (about 0.05 m/s), and consequently there appears to be a brief pause in conduction of about 80 ms at the AV node (that allows the atria to finish contracting before the ventricles begin), where the ECG is at zero potential (isoelectric). The wavefront then emerges on the other side of the AV node and rapidly spreads to all parts of the inner ventricular surface via the His-Purkinje system at speeds of 2–4 m/s. The activation of the entire ventricular myocardium takes place in about 100 ms. [Note that these times vary by 10–30% with age, activity and gender. The measurement of these times on the ECG also depends on the observation location, or clinical lead.]

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 0.15 mV in amplitude. The QRS complex corresponds to electrical excitation of the two ventricles, and has a peaked shape approximately 1.5 mV in amplitude. The T wave corresponds to the repolarization of the ventricles. It varies greatly from person to person, but is usually 0.1–0.5 mV in amplitude

and ends 350–450 ms after the beginning of the QRS complex. The region between the QRS complex and the T wave, called the *ST segment*, is the quiescent period between ventricular depolarization and repolarization, and under normal circumstances should be isoelectric. Algorithms for detecting individual ECG beats invariably focus on the QRS complex because of its short duration (steep slope) and high amplitude make it the most prominent feature.

Although most of the clinically important information in the ECG falls between 0.05 Hz and 50 Hz, the bandwidth of the ECG is not rigidly defined. (This is in part due to the fact that the constituent waves vary in amplitude and length as the heart rate changes.) Furthermore, since a rigid set of clinical interpretations have been ascribed to small changes in the timing and amplitude of the different waves or features (which may be small in energy themselves), it is often important to apply filtering and transformation techniques that preserve the magnitude and phase of the ECG.

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 (or 50 Hz in some countries) and its harmonics due to power-line noise.

2.3 Arrhythmias

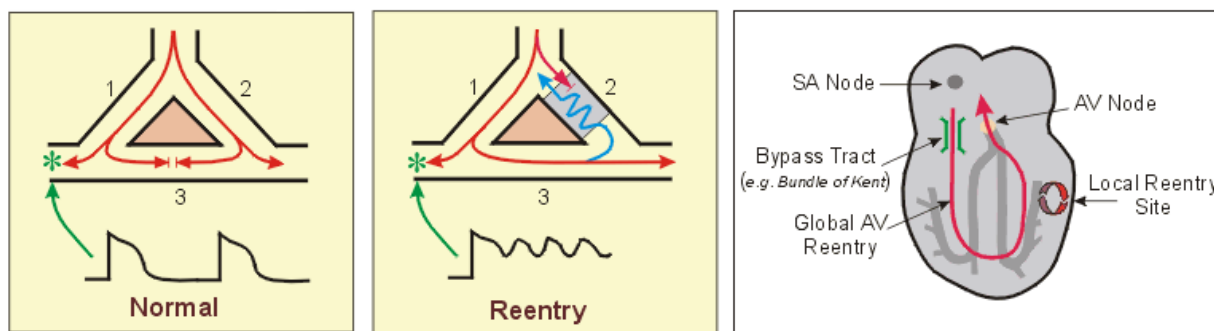
All normal heartbeats begin as an electrical impulse in the pacemaking tissue of the sinoatrial node, and a sequence of normal heartbeats is referred to as a *normal sinus rhythm*. The term *arrhythmia* refers to an irregularity in the rhythm. Most arrhythmias are associated with electrical instability 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.

Arrhythmias are, in general, caused by either ectopic foci (non-pacing cells acting as pace-

maker sites), or through a mechanism known as *reentry*. Reentry results from a conduction pathway loop that typically includes a region of blocked conduction and a region of slowed propagation such that when the action potential reaches the point of origin it finds tissue that is excitable, and an oscillation around the loop can occur one or more times. Reentry can take place within a small local region or it can occur, for example, between the atria and ventricles (global reentry). See figure 1.

In arrhythmia analysis, it is important to distinguish between atrial and ventricular arrhythmias. While the former can lead to annoying symptoms such as palpitations, angina, lassitude (weariness), and decreased exercise tolerance, ventricular arrhythmias are immediately life-threatening.



Courtesy of Richard E. Klabunde, Ph. D. Used with permission.

Figure 1: *Reentry* requires the presence of a unidirectional block within a conducting pathway (usually caused by partial depolarization resulting from ischemic, that is damaged and dysfunctional, tissue) and critical timing. Reentry can be local or global. Adapted from Klabunde.

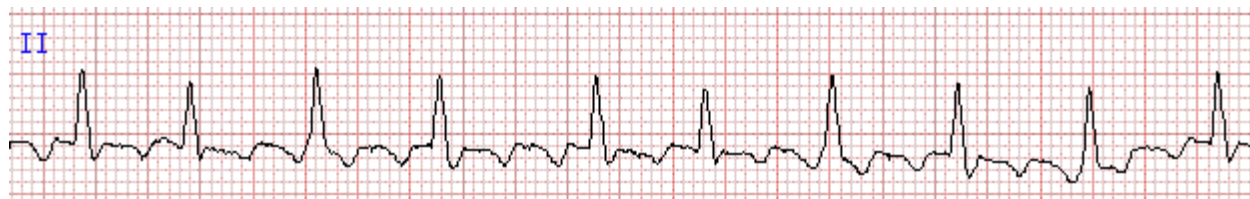


Figure 2: *Atrial Flutter*. P waves occur in rapid succession and each is identical to the next. Case 35 from Nathanson *et al.*

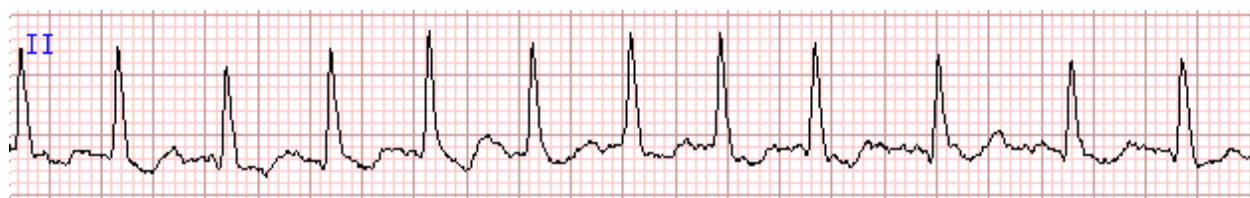


Figure 3: *Atrial Fibrillation*. Note the irregular atrial rhythm (timing for the P waves). In this case there is a rapid ventricular response (about 150/min) and non-specific ST-T changes can also be seen. Case 145 from Nathanson *et al.*

Courtesy of Ary Goldberger, M. D. Used with permission. Source: Nathanson L A, S. McClennen, C. Safran, A. L. Goldberger. ECG Wave-Maven: Self-Assessment Program for Students and Clinicians. <http://ecg.bidmc.harvard.edu>.

Atrial flutter (AFL) is thought to be caused by a reentrant rhythm in either the right or left atrium. A premature electrical impulse arises in the atria, and then differences in the tissue properties creates a loop of reentry moving along the atrium. In atrial fibrillation (AFib), the regular impulses produced by the SA node are overwhelmed by rapid, randomly generated discharges produced by larger areas of atrial tissue. AFL can be distinguished from AFib by the fact that AFL is a more organized electrical circuit that produces characteristic saw toothed waves on the ECG. AFL rates are typically 300 bpm with 2:1 AV conduction (two P waves for each QRS complex), resulting in a ventricular response rate of 150 bpm. (See figures 2 and 3.)

Two especially dangerous arrhythmias are *ventricular flutter* (VFL) and *ventricular fibrillation* (VFib). The most likely mechanism for these arrhythmias is reentry, although controversy remains concerning the exact underlying mechanism (Ideker and Rogers, 2006). In VFL the ventricles contract at such a high rate that there is not enough time for them to fill with blood, so there is virtually no cardiac output. (See figure 4.) Untreated VFL almost always leads to VFib.

In VFib, the chaotic twitching of the cardiac muscle prevents a coordinated pumping of the heart and leads to no cardiac output. (See figure 5) VFib is an emergency situation which requires treatment by electrical shock to restore the heart to a normal sinus rhythm.

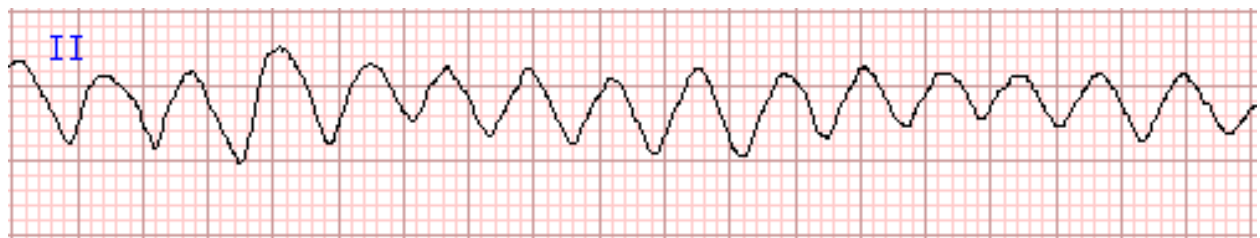


Figure 4: *Ventricular Flutter*. Notice the smooth sine wave appearance. Case 247 from Nathanson *et al.*

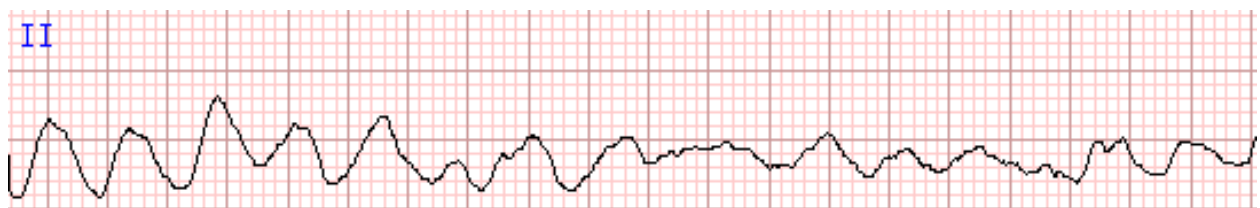


Figure 5: *Ventricular Flutter* almost always degenerates into *Ventricular Fibrillation* (as shown here) and requires cardiopulmonary resuscitation and defibrillation. VFib manifests as a chaotic twitching of the ventricles. Case 247 from Nathanson *et al.*

Courtesy of Ary Goldberger, M. D. Used with permission. Source: Nathanson L A, S. McClennen, C. Safran, A. L. Goldberger. ECG Wave-Maven: Self-Assessment Program for Students and Clinicians. <http://ecg.bidmc.harvard.edu>.

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

Clifford. G.D., *ECG Statistics, Noise, Artifacts, and Missing Data* in Advanced Methods and Tools for ECG Data Analysis, Artech House, October 2006. www/gari/ecgbook/ch3.pdf

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

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<http://www.cvphysiology.com/Arrhythmias/A008c.htm>

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Reisner, A., Clifford. G.D., Mark, R.G. *The Physiological Basis of the Electrocardiogram* in Advanced Methods and Tools for ECG Data Analysis, Artech House, October 2006. <http://alum.mit.edu/www/gari/ecgbook/ch1.pdf>

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

3 Specific Instructions

3.1 Data Acquisition

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 $V_{\max} = 5V$. 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).

*Note for OCW users: The necessary files and directories referenced herein have been provided in the supporting ZIP archives.

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 labeled 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, but it **will** depend on whether or not you have submitted nontrivial responses to **all** of the tutorial questions.

To register for a tutorial account, go to the URL that will be provided in class*. Once you have logged in to 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.

* OCW users: this URL is <https://repo.vanth.org/QuotaLinks/QbEWd> (requires free registration).

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 $-10.24 \text{ mV} - +10.235 \text{ mV}$.

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.

¹A *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 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)*

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)*