Electrocardiogram signal, acquisition, and analysis Lab

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Introduction

The purpose of this lab is to understand electrical biological signals, acquire the signal, and analyze the signal in digital form.

An electrical biological signal is produced from the electrical discharge of various cells in the body. Studying the electrical biological signals produced by the body is crucial to understanding its physiology.

During this lab, an electrocardiogram signal (EKG) is used- this signal is produced by a cascade of electrical signals that begin in the sinoatrial node (SA), located in the upper right atrium. The continuous signal produced by the heart must be converted into a form that a computer can analyze. To do this, the signal must pass through an analog to digital (A/D) converter, that transforms the analog signal to a discrete, binary signal. The binary signal is imputed into a computer software that provides a visual representation of the EKG signal. The EKG signal contains two major sections, depolarization and repolarization. The region of the EKG signal that represents when the signal from the SA reaches the right and left ventricles is referred to as the QRS complex (fig. 1).

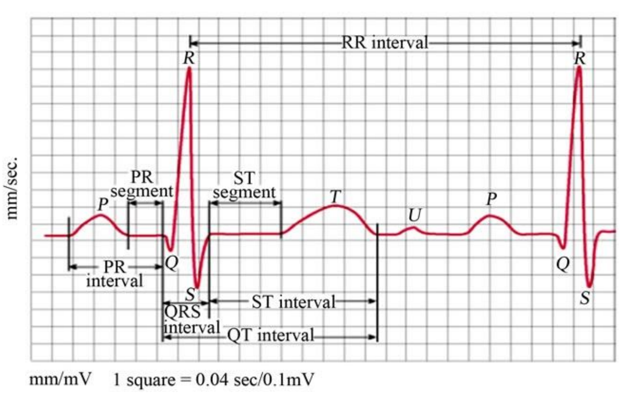

Fig. 1: A regular EKG signal with labeled regions (1).

To measure the EKG accurately, electrodes must be placed on the body according to Einthoven's Triangle (fig. 2). We tested numerous locations and placed the electrodes according to the accuracy of the signal produced.

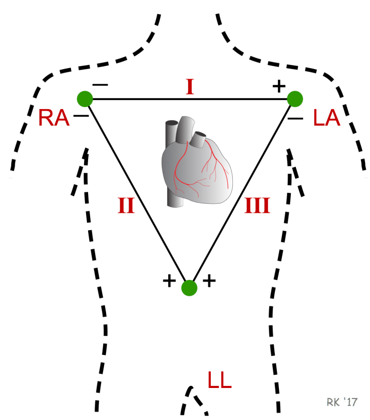

Fig. 2: Einthoven's triangle is roughly a equilateral triangle created by the standard lead (electrode) placement (2).

Methods

To begin the experiment, the lab provided electrodes, wires connected to an A/D converter, and a computer with needed software.

Condition One/Two

In order to determine the most advantageous electrode location, the team attached electrodes to various locations on Kim's body. According the Einthoven's triangle, the electrodes were placed with the negative lead on right proximal regions of the body and the positive lead on left distal regions of the body. In order to maintain consistency throughout all of the testing, the participant sat in the same location maintaining a calm and still composure, while the other participant changed the leads accordingly. Five separate combinations of negative-positive lead locations were tried and chosen from.

Initially, the negative lead was attached to the right elbow region and the positive lead to the left elbow region. Secondly, the negative lead was attached to the right shoulder and the positive lead to the left elbow. The third and fourth round of testing included negative and positive leads attached to right and left shoulders. Two runs were completed of this configuration due to an error in the first trial run. The participant laughed 22-25 seconds into the run, which resulted in an increase in the frequency of the heart beats. The fifth test included the negative lead attached to the right shoulder while the positive lead was attached to the left ankle. Lastly, the negative lead was attached to the right elbow and the positive lead to the left ankle.

The resulting EKG signals were uploaded into the provided computer with the standalone software needed for the EKG instrument (Loggerpro). The software enabled the team to view the signals on a time vs. voltage graph. The team ran the software with a sampling frequency of 250 hz over 60 seconds. The team then compared the resulting graphs of each lead location and determined the lead locations that provided the cleanest, consistent graph. The team chose the negative lead attached to the right shoulder and the positive lead attached to the ankle. To determine the accuracy of the choice, it may have been advantageous to do a second run on the chosen leads. We acknowledge that more data would have lead to higher accuracy in our choice. It is possible that there may have been better positioning of the electrodes. However, the data derived from our chosen leads provided good results regardless of our lack of double checking.

Condition Three

Once the lead configurations were determined, the participant was asked to do aerobic exercises for 60 seconds. Immediately following the exercises, the wires were connected to the chosen electrodes and 60 seconds of EKG signals were recorded.

Condition Four

We then asked the participant to perform the Valsalva maneuver. The participant was allowed a two minute break before performing this next step. The Valsalva maneuver is performed by forcing exhalation with closed airways- normally carried out by closing the mouth, pinching the nose, and attempting exhalation. The Valsalva Maneuver causes characteristic changes in systemic blood pressure, which should in turn change the frequency of the heart beat (1).

Condition Five

Lastly, the sampling frequency on Loggerpro was decreased to 5 hz. This test was performed with the consistency from the first runs, with the participant sitting, maintaining a cool composure. By decreasing the sampling frequency to less than twice the heart beat frequency, the QRS complex was lost in the graph.

Analyzing the Data

To view the data for condition one, the data was exported from Loggerpro to excel. In excel, an offset was added to the various location assignments, in order to view the multiple EKG signals on one graph. For the first column (Relbow-Lelbow), second column (Rshouder-Lelbow), third/fourth column (Rshoulder-Lshoulder), fifth column (Rshoulder-Lankle), and sixth column (Relbow-Lankle) -1,0,1,2,3,4, and 5 was added respectively. By doing this, the team could chose a condition that best suited the viewing of the EKG signal.

For the following questions of the lab hand-out, the team used Matlab to view and analyze the data.

Results & Discussions

Part One

01)

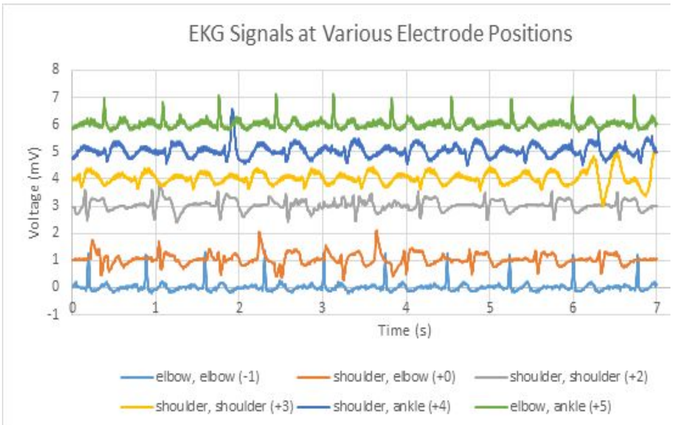

Fig. 3: EKG signals for 7 seconds from 6 different electrode positions as shown in legend. The voltages were offset by certain numbers (shown in legend) to display signals better.

Shoulder to ankle is the least noisy of the 6 EKG signals in Fig. 3, so we used that positioning in the next few condition.

02)

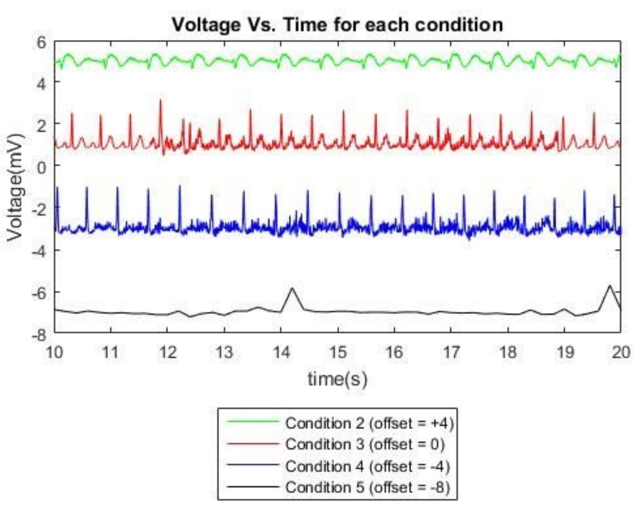

Fig. 4: EKG signals for four conditions described in detail in the methods section. Condition 2 - resting state EKG. Condition 3 - EKG after exercise. Condition 4 - EKG after valsalva maneuver. Condition 5 - EKG with 5 Hz sampling frequency.

03)

From our experiment, our subject had a maximum heartbeat of 114 beats per minute and a minimum heartbeat of 90 beats per minute, which corresponds to 1.9 Hz and 1.5 Hz respectively. These numbers were calculated using the preceding graph.

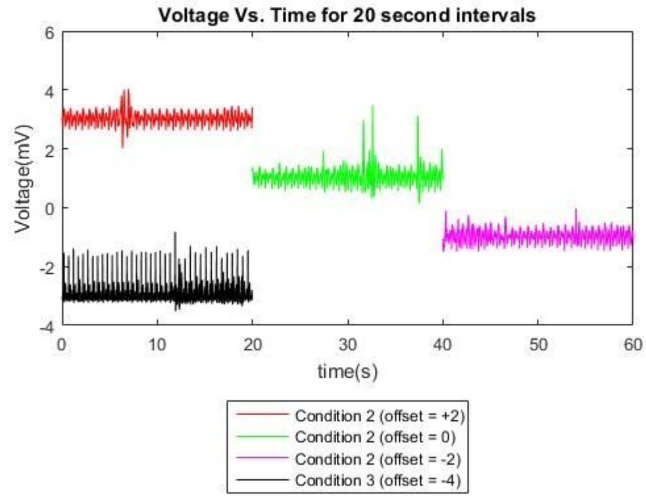

Fig. 5: Condition 2 and 3 EKG signals in 20 second windows.

According to a study on the time dependence of ventricular refractory periods, the absolute refractory period of the cardiac muscle is 250-300 ms (2). This means that the cardiac muscle is limited to a max of 200-240 beats per minute; the range depending on the age, weight, height, and gender of the person. This number represents the maximum number of beats per minute that the cardiac muscle can perform before failure, so this would take place during maximal work. Heart rate is limited by to two basic principles of electricity, the conductivity of the SA fibers and cardiac muscle fibers. As well as that limitation, the heart rate is also limited physiologically by the mechanism of the contraction.

04)

Right after vigorous exercise, the heart is trying to re-oxygenate the body's tissues, so it pumps blood through the body faster. So, the bpm is the highest,114, during this time and in fig. 5.

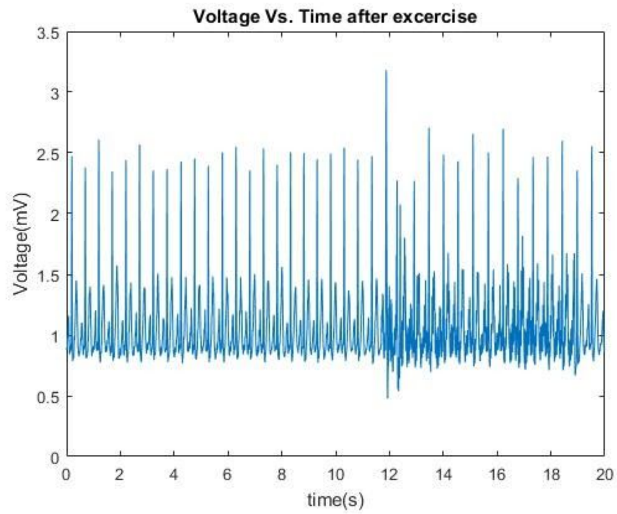

Fig. 5: 20 seconds of EKG after exercise.

05)
Amplitude of our teammate's EKG mostly varied between 1 and 3.5 mV throughout the various conditions. Within a sample, our teammate's EKG amplitude varied less than 0.5 mV. However, when our teammate was disturbed during the valsalva maneuver, his EKG amplitude changed dramatically. Other teams also got similar results. Specifically, Anna Craig's team had an average EKG amplitude of 2.5mV. This is reasonable because everyone's heart has to regulate it's voltage with great specificity. If it didn't, consequences on blood circulation would be drastic.

06)
Signal from condition 4 is the noisiest. Because it included the valsalva maneuver, which is a mechanism to reset the heart, voltage across the body would have been going haywire. We recorded little peaks and troughs between the heartbeats that should be there.The signal also has an offset because voltage never goes to 0 in our bodies. It changes across one value. In this EKG, it turns out to be about 1mV.

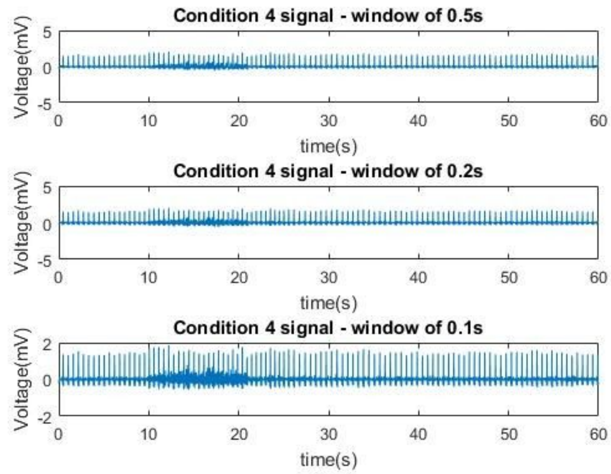

Fig. 6: EKG before, during, and after valsalva maneuver. Running average filters of various lengths as described in figure.

The running average algorithm with a window of 0.2 seconds reduces the most noise without losing the peaks or troughs in the signal. Below is a comparison of of the signal before and after it went through the algorithm.

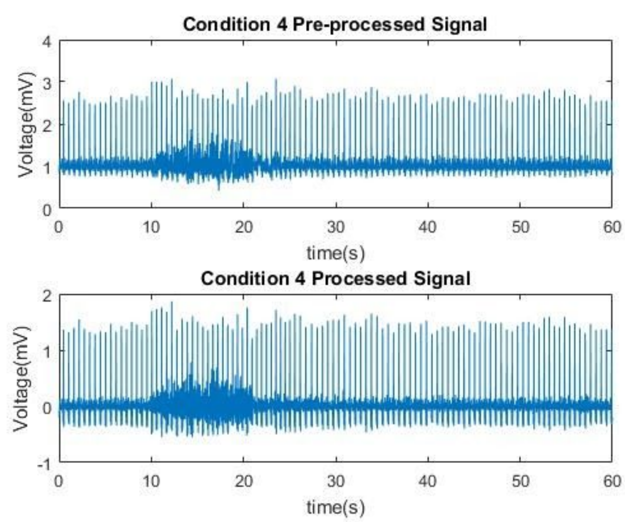

Fig. 7: EKG before and after applying the running average algorithm.

The running average algorithm is good for decreasing noise. It is simple and easy to use once the averaging window is optimized. However, it fails to remove noise during the first and last few seconds of the signal because during that time, there is no time window before or after the signal to find averages of. Also, when a signal changes direction or has a peak or trough removing the running average from the local or global maximum or minimum value would truncate the peak. There are more sophisticated algorithms where the averaging windows are changed based on how close in values the numbers are to each other. This would eliminate the second problem of truncating peak.

Part Two

01)
The electrical signal picked up the ECG is essentially from the action potential generated by the heart. If the heart was to fire action potentials at its maximum rate, which is a 1000 Hz, we would not be able to accurately record and represent the signal using a sampling frequency of 250Hz. Every time a signal is sampled, four cycles of the action potential signal would have passed. In order to sample a signal that can be reconstructed to an accurate representation, a faster sampling frequency must be used. This idea can also be explained through the Nyquist criterion, which states that our signal frequency must be less than half of our sampling frequency to prevent aliasing and getting an incorrect signal. Since our sampling frequency is one-fourth of our signal frequency, this tells us that we cannot accurately sample this signal using 250 Hz.

While a signal with a frequency of 1000Hz cannot be sampled with a sampling frequency of 250Hz, the signals we detected were significantly lower than this frequency. For condition 2, the signal frequency was only 1.4Hz. This satisfies the Nyquist criterion and thus was accurately sampled to give an accurate picture of our signal.

02)
To compare the ECG signal to a sinusoidal wave, a cycle from the ECG signal of condition 2 (Shoulder to ankle) was used. Below is a plot of the signal and one cycle of the sinusoidal wave. The peak of the signal (R – component) coincided with the sine wave, both in time and magnitude.
(2.32 mV, 15.548 s)

The S – component of the signal also coincided with the sine wave in magnitude.(0.8 mV).

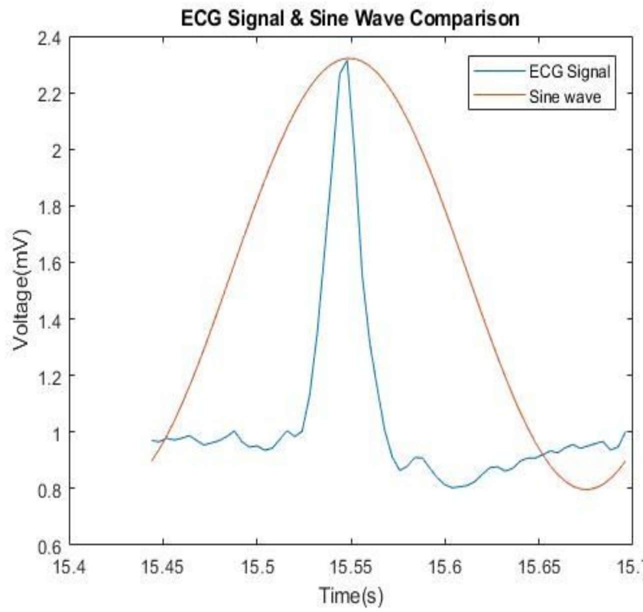

Fig. 3: One cycle of the ECG Signal for Condition 2 (Shoulder to Ankle) plotted with a Sine wave using MATLAB.

The sinusoidal wave used to plot the graph had the form of Asin(2πf(signal)nt(sampling) + w) + B, where each abbreviation represented the following:

A : Amplitude
f(signal) : signal frequency
nt(sampling) : discrete time
w: Phase
B: offset

Amplitude was calculated by taking mean voltage values over the period of the signal with slight adjustments to coincide the R and S components with the peak and trough of the sine wave. Signal frequency was calculated by taking the inverse of the period of the signal.
Phase was given a number that would allow the peak of the sine wave to coincide in time with the R- component of the signal.
Offset was calculated by taking the absolute values of the maximum and minimum values of the signal and taking the average of the two to find the midpoint at which the sine wave is centered.

Appendix

Part One

```
clear all; close all; clc;
C1 = xlsread('condition1.csv');
C2 = xlsread('condition2.csv');
C3 = xlsread('condition3.csv');
C4 = xlsread('condition4.2.csv');
C5 = xlsread('condition5.csv');
% Question 2
% We plotted 10s - 20s of data from each condition
% Most graphs for each question that have legends also
have offsets so
%         each graph is better displayed.
figure(2) % Question 1 is associated with figure 1
title('Voltage Vs. Time for each condition');
xlabel('time(s)');
ylabel('Voltage(mV)');
% used 'C1' for condition 2 because when we
transferred the data, C2 only
% saved 20s of data. We recorded all of C1 when our
team member for
% calmly resting, so for the rest of the data we will be
using the C1
% shoulder to ankle values saved in the 9th and 10th
rows.
y2 = C1(2501:5001, 10) + 4;
plot(C1(2501:5001, 9), y2, 'g');
hold on
plot(C3(2501:5001, 1), C3(2501:5001, 2), 'r');
hold on
y4 = C4(2501:5001, 2) - 4;
plot(C4(2501:5001, 1), y4, 'b');
hold on
y5 = C5(51:101, 2) - 8;
plot(C5(51:101, 1), y5, 'y');
legend('Condition 2 (offset = +4)', 'Condition 3 (offset =
0)', 'Condition 4 (offset = -4)', 'Condition 5 (offset = -8)')
legend('location', 'southoutside');
hold off
% Question 3
% Plot voltages at intervals of 20 seconds in Conditions
2 and 3. Count
% beats in the interval by hand. Multiply # of beats by 3
to get bpm.
% Divide bpm by 60 to get frequency of heart beats in
Hz.
figure(3)
title('Voltage Vs. Time for 20 second intervals');
xlabel('time(s)');
ylabel('Voltage(mV)');
% Plot of first 20 seconds of Condition 2 voltages
% We plotted this instead on the last 20 seconds of
Condition 3 voltages
% because we accidently didn't save the last 40 seconds
of data for
% Condition 3
h1 = C1(1:5001, 10) + 2;
plot(C1(1:5001, 9), h1, 'r');
% Found 32 beats.
% Plot of second 20 seconds of Condition 2 voltages
hold on
h2 = C1(5001:10001, 10);
plot(C1(5001:10001, 9), h2, 'g');
% Found 34 beats.
% Plot of third 20 seconds of Condition 2 voltages
hold on
h3 = C1(10001:15001, 10) - 2;
plot(C1(10001:15001, 9), h3, 'm');
% Found 30 beats.
% Plot of first 20 seconds of Condition 3 voltages
hold on
h4 = C3(1:5001, 2) - 4;
plot(C3(1:5001, 1), h4, 'y');
% Found 38 beats.
legend('Condition 2 (offset = +2)', 'Condition 2 (offset =
0)', 'Condition 2 (offset = -2)', 'Condition 3 (offset = -4)');
legend('location', 'southoutside');
hold off
% Max heart beat = 38 beats. Maximum = 3 * 38 = 114
bpm.
%                         Frequency = 114/60 = 1.9 Hz.
% Min heart beat = 30 beats. Minimum = 3 * 30 = 90
bpm.
%                         Frequency = 90/60 = 1.5 Hz.
MinimumHeartBeat_bpm = 90
MinimumHeartBeatFrequency_Hz = 1.5
MaximumHeartBeat_bpm = 114
MaximumHeartBeatFrequency_Hz = 1.9
% Question 4
% Plot to observe the Valsalva Maneuver
figure(4)
title('Voltage Vs. Time during Valsalva Maneuver');
xlabel('time(s)');
ylabel('Voltage(mV)');
plot(C4(:,1) ,C4(:,2));

% Question 6
% Noisiest Signal is produced during Condition 4
% This figure will show the signal at various running
average windows
figure(5)
% remove offset by subtracting the average of all
voltages in the array
new = C4(:,2) - mean(C4(:,2));
```

```
% running average is over 0.5 seconds. First index values I'll average over
% are 1 - 126. So, all the values below index 64 don't recieve an averaged
% value, and won't be processed.
analyC4 = zeros(15001,1);
for k = 1:15001
 if k <= 64 || k > 14937
        analyC4(k, 1) = new(k, 1);
 else
        avg = mean(new(k-64:k+64), 1);
        analyC4(k, 1) = new(k, 1) - avg;
 end
end
subplot(3,1,1);
plot(C4(:,1) ,analyC4);
title('Condition 4 signal - window of 0.5s');
xlabel('time(s)');
ylabel('Voltage(mV)');

% changed running average to over 0.2 seconds. First index values I'll average over
% are 1 - 51. So, all the values below index 26 don't recieve an averaged
% value, and won't be processed.
analy2C4 = zeros(15001,1);
for k = 1:(15001-25)
 if k <= 25 || k > 14976
        analy2C4(k, 1) = new(k, 1);
 else
        avg = mean(new(k-25:k+25), 1);
        analy2C4(k, 1) = new(k, 1) - avg;
 end
end
subplot(3,1,2);
plot(C4(:,1) ,analy2C4);
title('Condition 4 signal - window of 0.2s');
xlabel('time(s)');
ylabel('Voltage(mV)');

% changed running average to over 0.1 seconds. First index values I'll average over
% are 1 - 26. So, all the values below index 14 don't recieve an averaged
% value, and won't be processed.
analy3C4 = zeros(15001,1);
for k = 1:15001
 if k <= 14 || k > 14987
        analy3C4(k, 1) = new(k, 1);
 else
        avg = mean(new(k-14:k+14), 1);
        analy3C4(k, 1) = new(k, 1) - avg;
 end
end
subplot(3,1,3);
plot(C4(:,1) ,analy3C4);
title('Condition 4 signal - window of 0.1s');
xlabel('time(s)');
ylabel('Voltage(mV)');

% Below code displays pre- and post- processing signals
figure(6)
subplot(2,1,1);
plot(C4(:,1) ,C4(:,2));
title('Condition 4 Pre-processed Signal');
xlabel('time(s)');
ylabel('Voltage(mV)');
subplot(2,1,2);
plot(C4(:,1) ,analy3C4);
title('Condition 4 Processed Signal');
xlabel('time(s)');
ylabel('Voltage(mV)');
```

Part Two

```
signal = csvread('condition2.csv',3862,0,[3862 0 3925 1]);
plot(signal(1:64,1),signal(1:64,2));
hold on

f = 250;
A = mean(signal(1:64,2))-0.28;
t_sampling = 1/f;
offset = (abs(max(signal(1:64,2))) + abs(min(signal(1:64,2))))/2;

y_sample = zeros(64,1);
y_sample(1) = A*sin(17.800) + offset;

for n =1:63
y_sample(n+1) = A*sin((2*pi)*(1/0.252)*n*t_sampling + 17.800) + offset;
end

plot(signal(1:64,1),y_sample(1:64))
title('ECG Signal & Sine Wave Comparison')
xlabel('Time(s)')
ylabel('Voltage(mV)')
legend('ECG Signal','Sine wave')
```

Sources

Figures:

(1)Chandramouleeswaran, S. , Haidar, A. and Samsuri, F. (2012) Wavelet diagnosis of ECG

*signals with kaiser based noise diminution. Journal of Biomedical Science and Engineering, **5**, 705-714. doi: 10.4236/jbise.2012.512088.*
(2)Klabunde, Richard E. "Electrocardiogram Standard Limb Leads (Bipolar)." Image for Cardiovascular Physiology Concepts, Richard E Klabunde PhD, 22 Dec. 2017, www.cvphysiology.com/Arrhythmias/A013a.

Data sources:

(1)Tiecks, Frank P., et al. "Effects of the Valsalva Maneuver on Cerebral Circulation in Healthy Adults." Stroke, American Heart Association, Inc., 1 Aug. 1995, stroke.ahajournals.org/content/26/8/1386.
(2)Strobel, Fisher, Katz, Kim, & Mercando. (1990). Time dependence of ventricular refractory periods: Implications for electrophysiologic protocols. Journal of the American College of Cardiology, 15(2), 402-411.