# **ECG Signal** Denoising Through Two Ways

When I was looking for a specific application that was related to digital signal processing, I found the electrocardiographic (ECG) signals and its denoising process. The wave characteristics of ECG signal indicate the possible symptom of heart disease; in addition, it is increasingly common that cardiac disorders caused from many kinds of reasons are killing people. Recognizing abnormal heart rhythm through ECG signals allows doctors to make predictions and judgements on heart conditions evaluation and provide timely treatment. However, ECG signal collected from the human skin is contaminated by different sources of noise. Therefore, I carried out this research on the denoising of ECG signals in both acquisition and processing stage.

## Problem

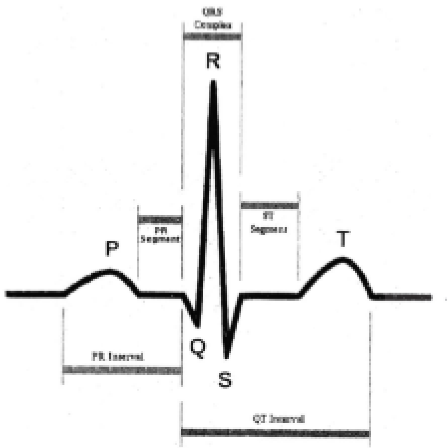
Electrical activities of the heart can be picked up via **electrodes** connecting to a ECG machine which records signals and convert them into graphics. However, there are several problems in the process that make visual inspection and ECG feature extraction from ECG signals difficult:

1. The collected ECG signal is very weak and can be easily affected by noise.
2. The main components of the various waves should be retained during the denoising process, but the ECG signal is composed of several waves of different waveforms. Moreover, the interference signal overlaps the frequency band of the ECG signal.
3. There are many noise components, therefore which denoising method to choose is based on the specific situation.

## Theory

### *Components of ECG signal*

ECG is a time-domain signal composed of potential changes caused by activities of the heart. The ECG signal is measured from the chest cavity or body surface by using electrodes, and the analog signal is digitized to trace the collected waveform signal.
A normal ECG signal is roughly composed of P wave, QRS complex, T wave, and the intervals and segments between them, as shown in the figure below:




- P wave represents the sequential activation (depolarization) of the right and left atria, with an amplitude that usually does not exceed 2.5mV and a duration of no longer than 1s.
- QRS complex represents the process of  right and left ventricular depolarization. R wave is the main wave of the complex, and the length of time normally it is 0.06~0.1s. R wave amplitude is generally 0.4~2.4 mV, while Q wave generally does not exceed 0.3mV.
- ST segment is the waveform change from the end of QRS complex to the beginning of the T complex. There is no potential difference between the parts, so the normal ST segment is level with the baseline.
- T wave represents ventricular repolarization. The amplitude is 0.1~0.8.8mV, and the time length is 0.05~0.25s.

## *Sources and types of noises*

In general, ECG contaminants can be classified into different categories:

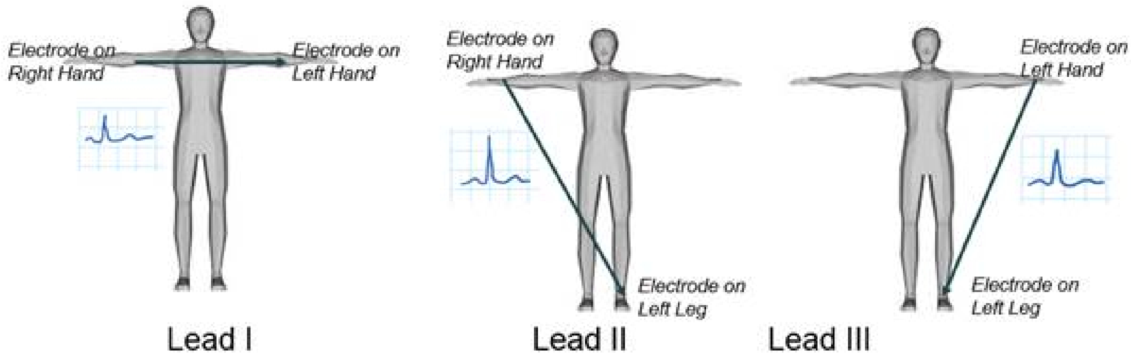
- **power line interference(PLI)工频干扰**
- **electrode pop or contact noise电极接触噪声**
- **patient-electrode motion artifacts运动伪迹**
- **electromyographic (EMG) noise肌电干扰**
- **baseline wandering基线漂移**

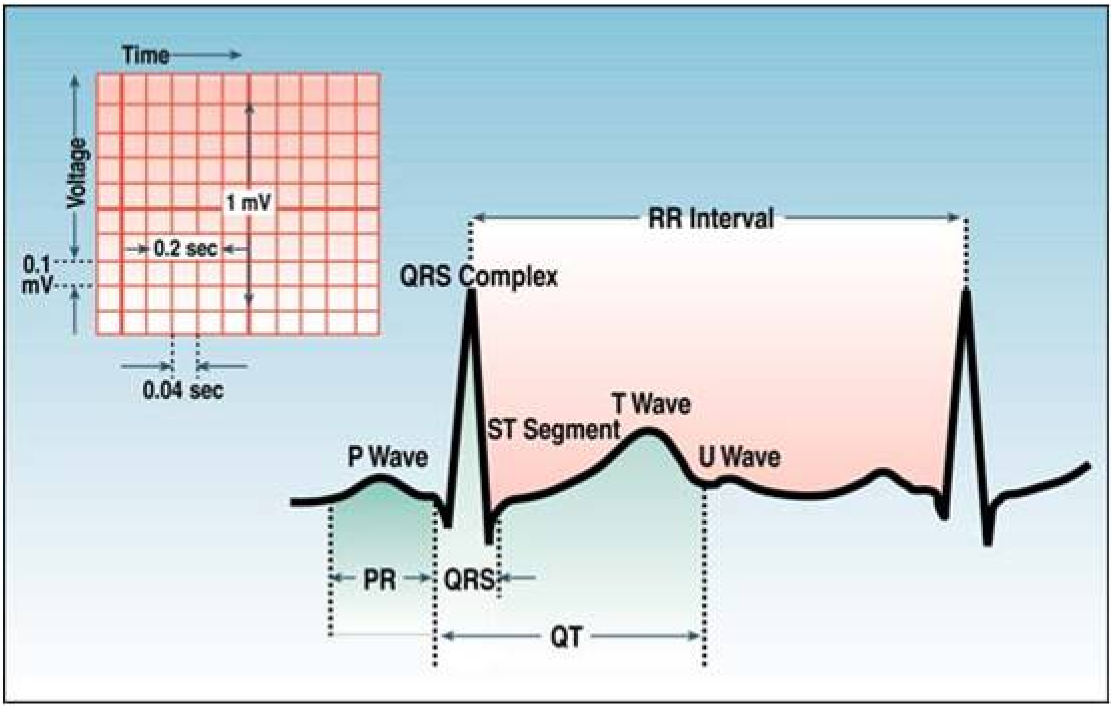
Among these noises, the power line interference and the baseline wandering (BW) are the most significant and can strongly affect ECG signal analysis. Except for these two noises, other noises may be wideband and usually involve a complex stochastic process, which also distorts the ECG signal. The power line interference is narrow-band noise centered at 50 Hz or 60 Hz with a bandwidth of less than 1 Hz. Thus, denoising this type of signals is decisive for further parameter extraction in clinic applications.

| 噪声种类 | 频率/频率成分 | 幅度 | 持续时间 |
| --- | --- | --- | --- |
| 工频干扰 | 50/60Hz | <=ECG 峰峰值的 50% | ---- |
| 电极接触噪声 | 60Hz | 记录器最大输出 | 1s |
| 运动伪迹 | | ECG 峰峰值的 50% | 100-500ms |
| EMG 干扰 | DC-100Hz | ECG 峰峰值的 10% | 500ms |
| 呼吸系统引起的基线漂移和心电图幅度的变化 | ---- | 幅度变化：ECG 峰峰值得 15%；基线变化：0.15-0.3Hz 为 ECG 峰峰值的 15% | ---- |
| 电子设备的干扰 | ---- | ---- | ---- |
| 电外科噪声 | 100K-1MHz | ECG 峰峰值得 200% | 1-10s |

# Acquisition

When checking patient's heart's rhythm and electrical activity, sensors are attached to the skin, and they detect the electrical signals produced by patient's heart each time it beats. Patients are need to remove his/her upper clothing to expose the skin, and keep chest clean. During signal acquisition, the electrodes need to stay where they are in place, in order to reduce Skin-Electrode interlace noise.  The test usually lasts a few minutes.




# *Game Solution*

**Abstract Idea**

When the player is having an ECG, with electrodes sticked to the arms, legs and chest, he/she will solve puzzles that can grab his/her attention from the test itself. In this way, electrode contact noise can be reduced because the patient feel peace and forget about the anxiety and nervous about test.

**What is the game play sound like?**

The player is given a candy with a puzzle printed on the wrapper when entering the room. He/she lies on the bed, and the doctor put electrodes on the player's body, including his/her chest, arm and leg. After that, the player can observe the stickers that are projected on the screen. Each stick represents a piece of information. The player rolls his/her eyes to select options and chooses his  answer by blinking. The puzzle takes about a few minutes to solve.

**Who is the audience for your game?**

Children who is having a ECG or people who are over concerned about such a medical examination and need distractions.

**How many players can play (give a range)?**

**What do you want the game to feel like (silly, strategic, tense, etc.)**

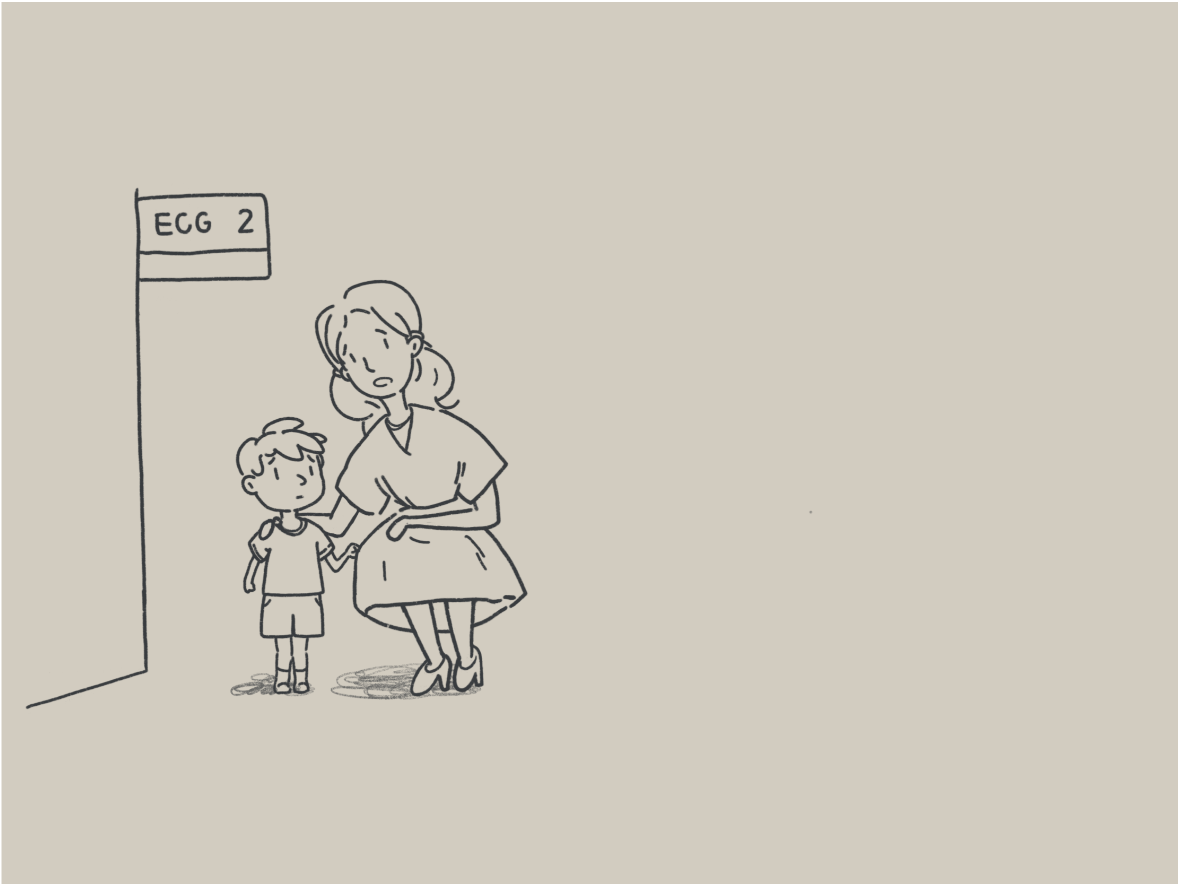
relaxing, attracting, attention-grabbing, peace, concentrated, short-period, a little fun

**What makes this game different from other games?**

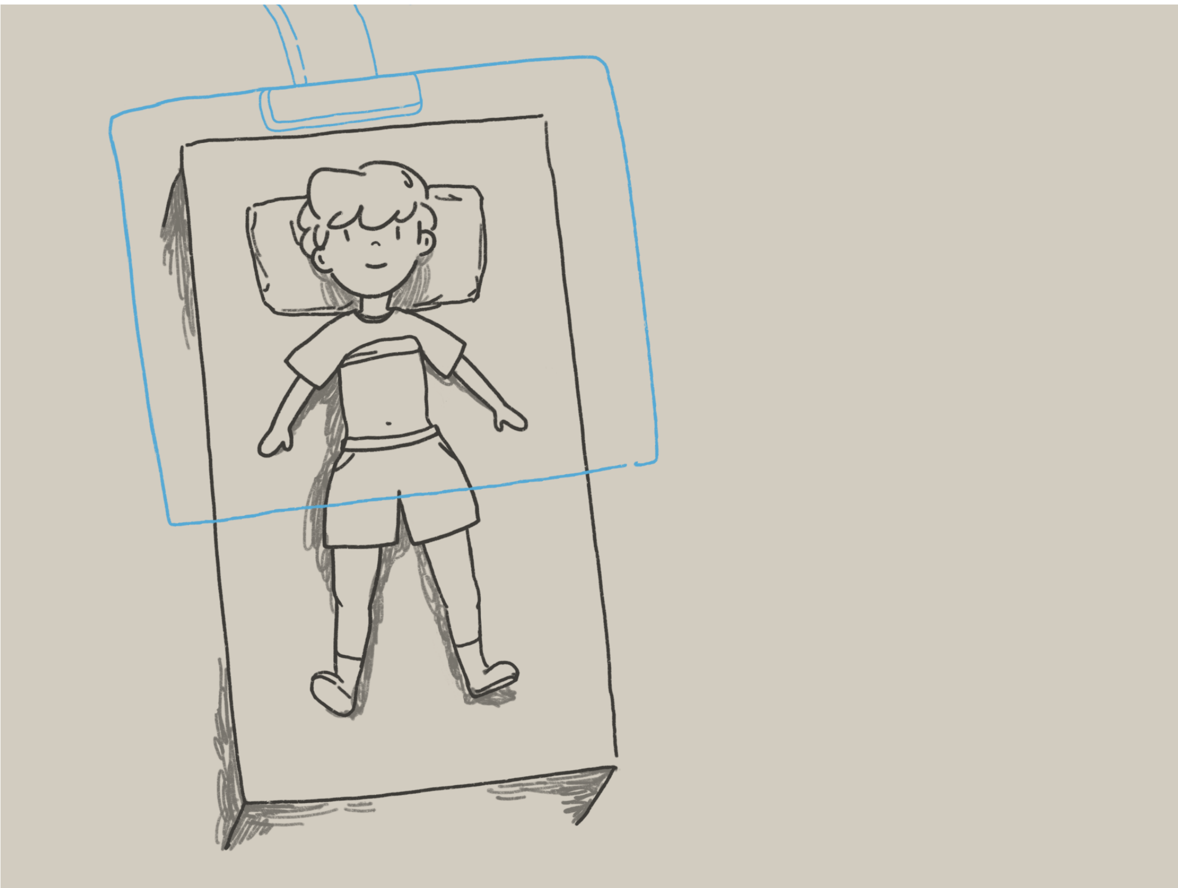
The environment of the game is in a hospital's ECG room, and it helps the ECG recording machine collect information about heart's rhythm and electrical activity more accurately. Moreover, the game distracts the players down and reliefs their nervousness and embarrassment.

For example, a child is going to take an ECG at loal children's hospital.

*Before*




*After*



## Signal Processing

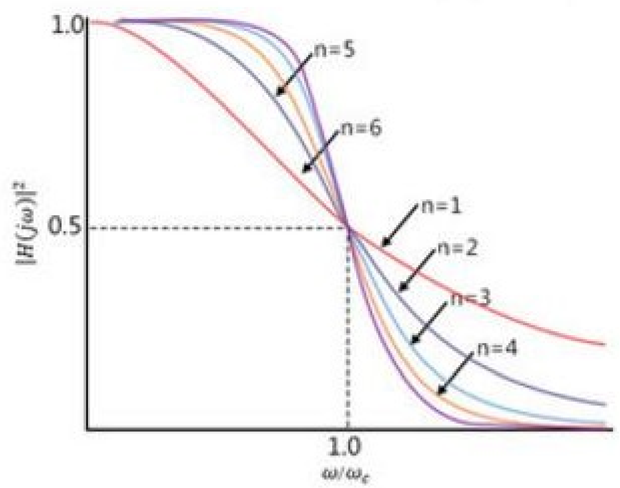
For processing ECG signals, it is necessary to remove the several types of contaminants mentioned above from these signals. According to the noise type and characteristics, we can choose ECG denoising approaches.

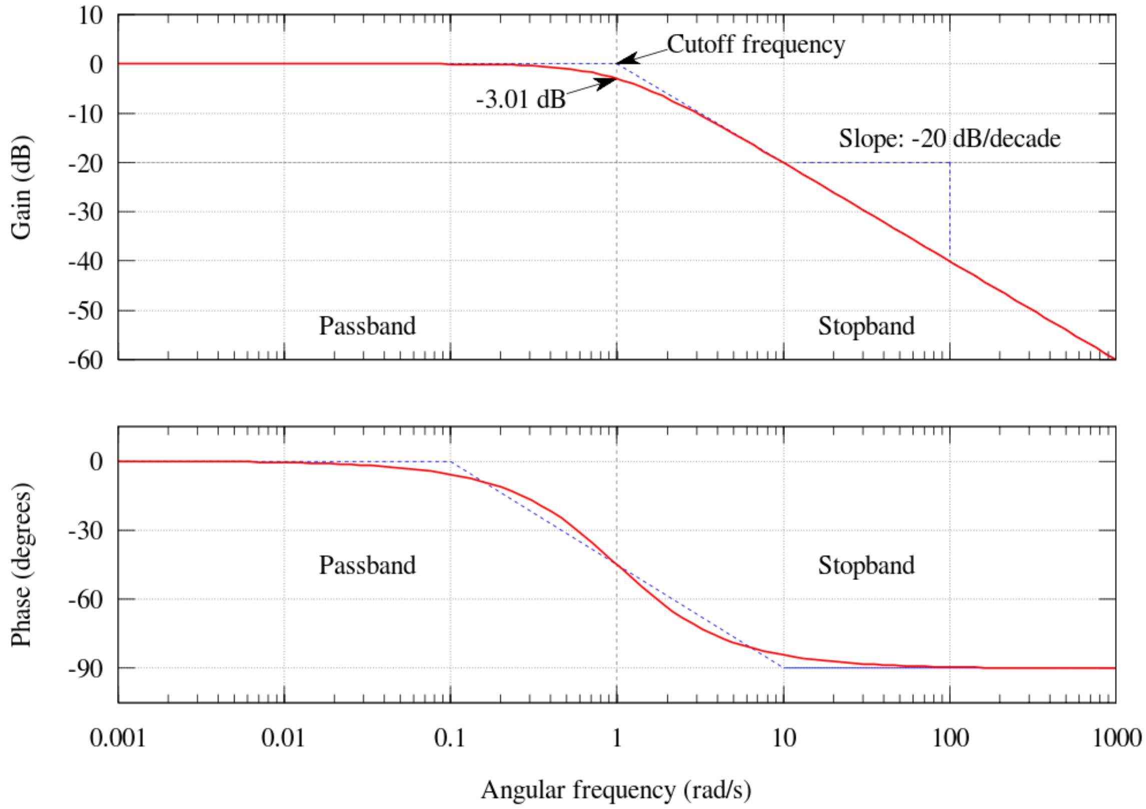
For the removal of PLI, choose smoothing filter, adaptive filter and discrete wavelet transform(DWT) respectively and observe the denoising result:

− *The smoothing filter that comes with Matlab is a low-pass filter whose filter coefficient is equal to the reciprocal of the span.*
− *The general principle of the adaptive filter is to obtain the signal component by subtracting the interference signal component from the signal. If the frequency of the interference signal in the original signal (such as the most common 50Hz power frequency interference) is known, the phase and amplitude of the interference signal are obtained and subtracted from the original signal.*
− *Discrete wavelet transform(DWT) uses wavelet functions to decompose the signal in multiple layers, which allows representing a signal by a finite sum of low-frequency and high-frequency wavelet coefficients at different resolutions. Therefore, each component can be denoised with different thresholds and then used to reconstruct the signal.*

For baseline wandering, because it will have a great impact on the correct detection of the ST-T segment, it is necessary to reduce the amplitude and phase distortion of the ECG signal when denoising, so as to avoid the obvious deformation of the low-frequency parts such as the ST segment and cause detection distortion. A zero-phase filter is used to correct it. The zero-phase filter uses the information contained in the signal points before and after the current signal point to eliminate phase distortion.

For EMG interference, which is manifested as high-frequency noise, it is removed using a Butterworth low-pass filter. The Butterworth filter makes the frequency response curve in the pass band to be as flat as possible, and gradually drops to zero in the stop band.



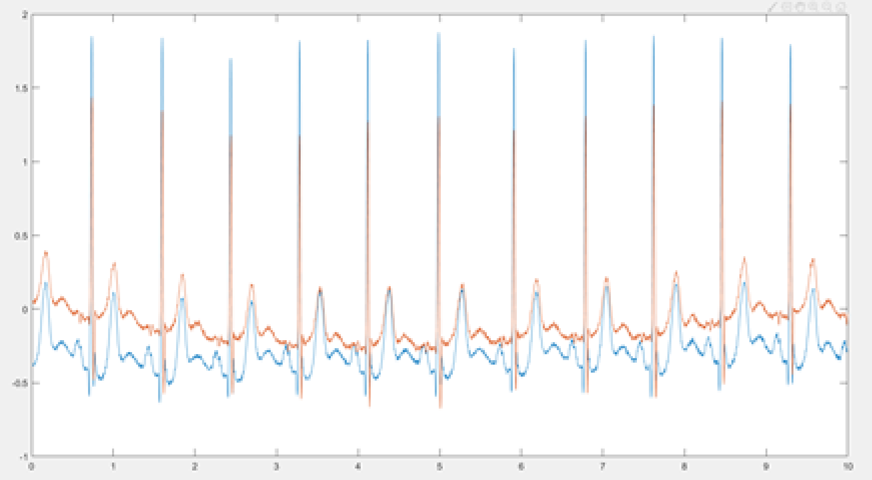




The Bode plot of a first-order Butterworth low-pass filter

# *Experiment*

In the experiment, I took the original ECG signal in the MIT-BIH Arrhythmia Database as input, tried several denoising approaches in signal processing and compared the results, selected the best method, and detected the peaks of the denoised signal to evaluate results. The MIT-BIH Arrhythmia database contains 48 half-hour excerpts of two-channel ambulatory ECG recordings, obtained from 47 subjects between 1975 and 1979 by the Beth Israel Hospital Arrhythmia Laboratory. The data is identified and labeled by cardiologists, which can be used as standard test material for evaluation of arrhythmia detectors.

First, read the .dat, .hea, .atr files, and obtain the basic information of the same ECG signal by byte, and the corresponding byte. (The  data reading method refers to rddata.m by Robert Tratnig).The sampling frequency Fs is 360Hz and the sampling number Fn is 3600. Read ten seconds of the original signal as shown in the figure:



The original signal is collected with dual channels. In the following experiment, I chose one of them for signal processing and analysis.

## Removal of Power Line Interference

### Smoothing filter

Use a moving average filter to smooth the signal:

$$Z = smooth(Y, SPAN)$$

The first parameter Y is the input signal, and the second parameter SPAN is the window width of the average moving filter. The continuous sampled data is regarded as a queue with a fixed length of N. The function returns a moving average of the elements of a vector using a fixed window length that is determined heuristically.

Take different values for window width as 3, 5, 9, 11:

```
SMOOTH_signal = smooth(m,3);
SMOOTH_signal = smooth(m,5);
SMOOTH_signal = smooth(m,9);
SMOOTH_signal = smooth(m,11);
```

### Adaptive Filter

Adaptive filter is a system that adjust parameters to control the filter according to an optimization algorithm. In denoising process, the goal is to extract the true and accurate expected signal from the observed signal. Thus the relevant parameters include input signal x, expected signal d, and the Filter order M.

For a Mth order filter with parameter w(m), the output y is calculated as

$$y(n) = \sum_{m=0}^{K} w(m)x(n-m)$$

The error signal is

$$e(i) = d(i) - y(i) = d(i) - w^T(i) * x(i)$$

The error signal e(x) is minimized when the mean square ((d(i)- w^T  (i)*x(i)))^2 is minimized which is a common form of cost function.

```
lms = LMS(m,signal);
```

### Discrete Wavelet Transform

The first step is to choose a wavelet type--for example, db5 and db8, and a level N of decomposition. Next, select and apply thresholds for each level from 1 to N. As for the quantization of the threshold, here I used a soft threshold function. The final step is to reconstruct the signal with detail coefficients and approximation coefficients.

I chose db5 and db8 as wavelet type in the experient:

```
softDWT_5 = dwt5signal(m);
softDWT_8 = dwt8signal(m);
```

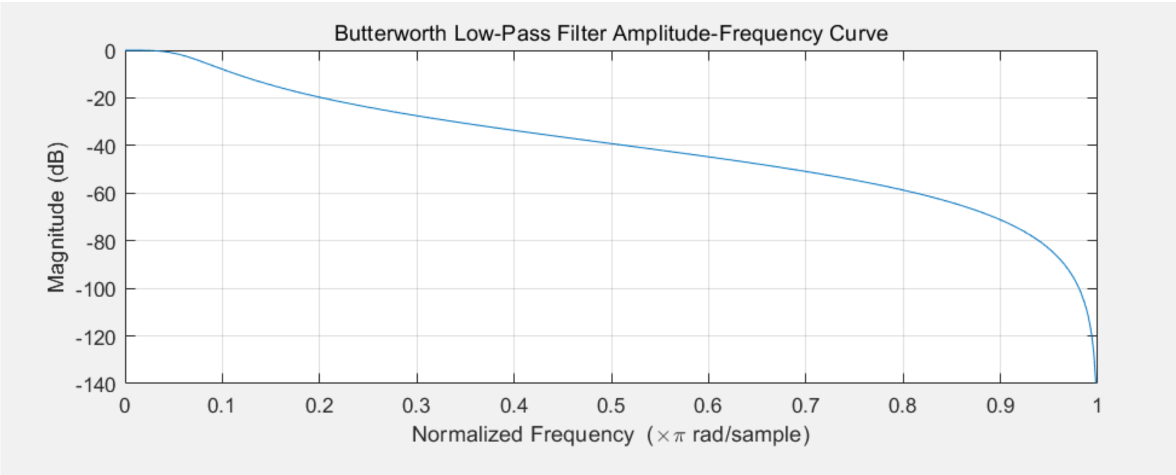
## Removal of Baseline Wandering

Apply an Infinite Impulse Response(IIR) filter to remove the impact of baseline wandering. The implement of IIR is to use an elliptic filter. The reason is that for the same transition band index, the elliptic filter requires less number of orders compared to other types of filters, but is the most sensitive to coefficient quantization. In this process, use a low-pass filter with following parameters:

sampling frequency = 3000Hz, passband cutoff frequency = 1.4*2/FsHz, stopband cutoff frequency = 0.6*2/FsHz, passband attenuation = 1.0, stopband attenuation = 1.5, and passband ripple = 0.005 .

## Removal of Electromyographic Noise

To remove the electromyographic noise, apply a Butterworth low-pass filter to filter out high-frequency noise. Use a low-pass filter with a sampling frequency of 3000 Hz, a passband cutoff frequency of 100 Hz, and a stopband cutoff frequency of 110 Hz where the passband attenuation is 1.0 and the stopband attenuation is 1.5.




# *Analyse*

The MIT-BIH database contains 48 half-hour excerpts of two-channel ambulatory ECG recordings. In order to have a better observation of noise reduction effect, the selected signals have specific features as follows:

109.dat: The waveform of the signal is relatively uniform with intermittent noise.

103.dat: The signal has waves with varying amplitudes. The R wave is narrow and towering, but the Q wave and S wave are not obvious, and they can be easily removed in denoising process.

102.dat: The R wave has an abnormal waveform.

104.dat: The signal is very different from the normal ECG signal, and the main R wave characteristics are not obvious.

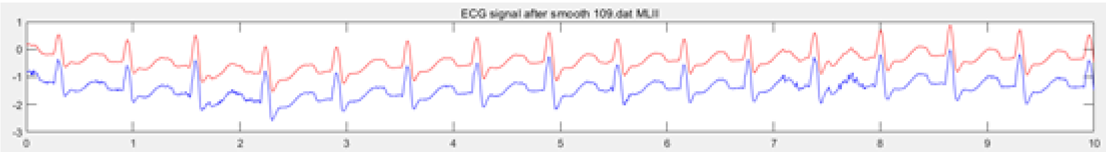
In the following figures, the original signal is shown as the blue curve and  the output signal is shown as the red curve.

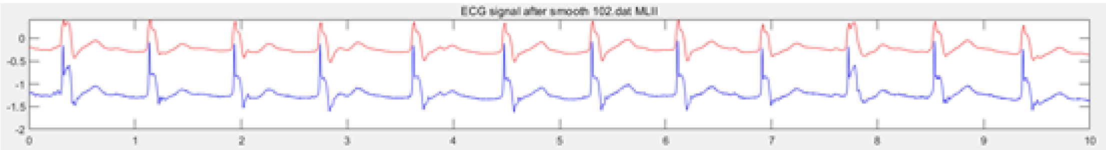
# Step 1 PLI

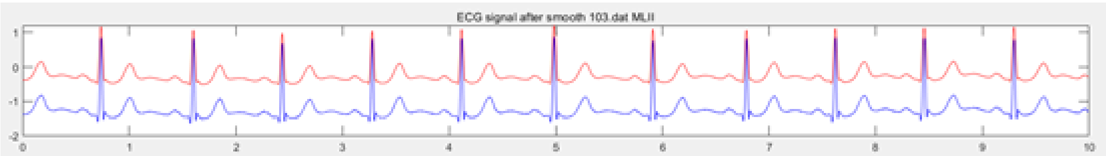
## Smoothing filter

Apply a smoothing filter to 109.dat, 102.dat, and 103.dat with different span values (the signal is vertically shifted by one unit):

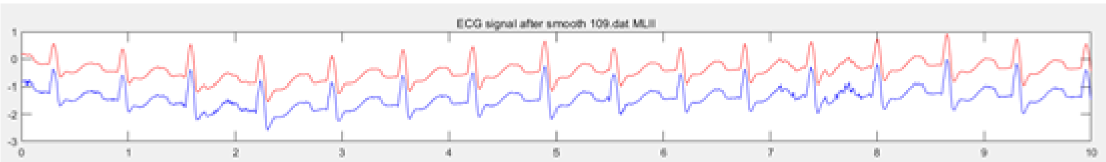
SPAN=11

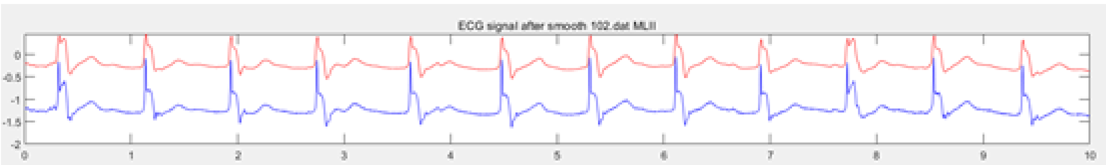


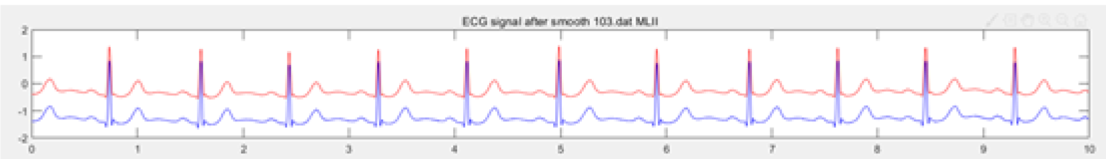



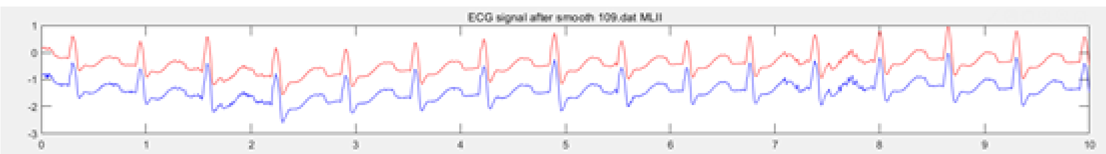

SPAN=9

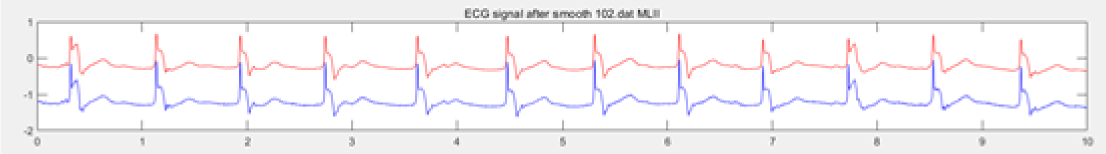


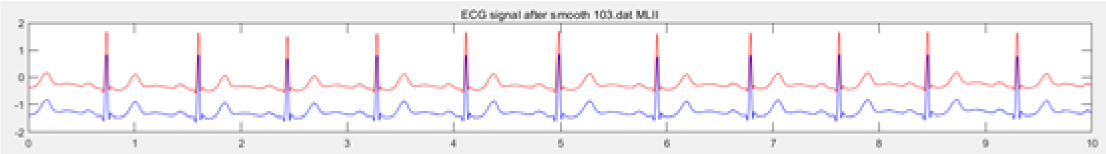



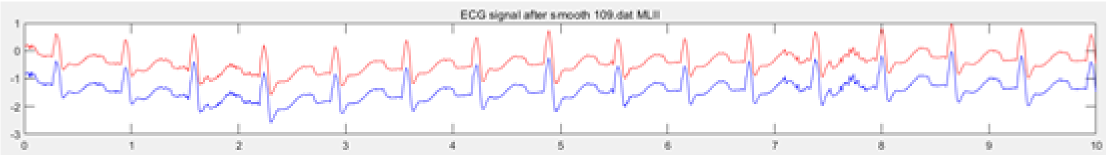

SPAN=5

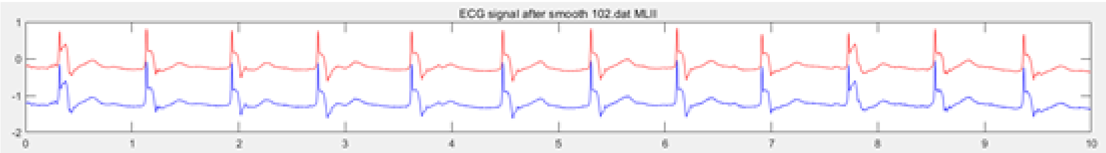


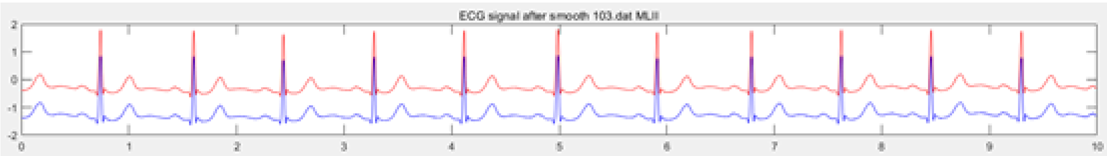



SPAN=3



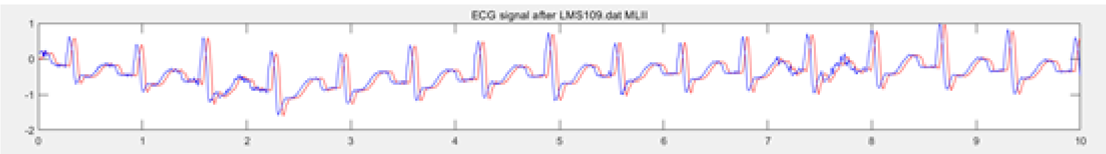



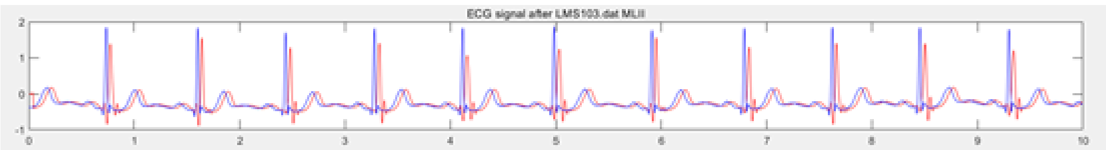



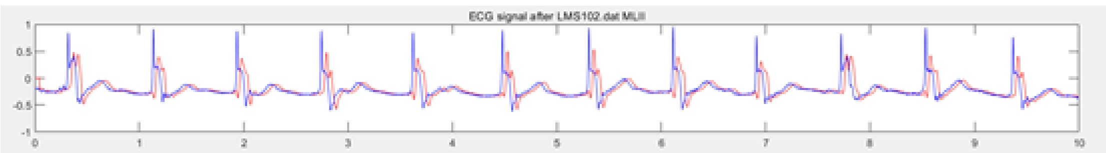

According to the results, when SPAN is 9 or greater, smoothing filter is relatively effective in denoising in intervals and segments, but there is some signal distortion in QRS complex, which results from replacing the instantaneous value with the local average value. When SPAN=5 or less, the waveform of QRS complex is better retained.

## Aptive filter

Use an aptive filter to process the signal and the results are shown below：



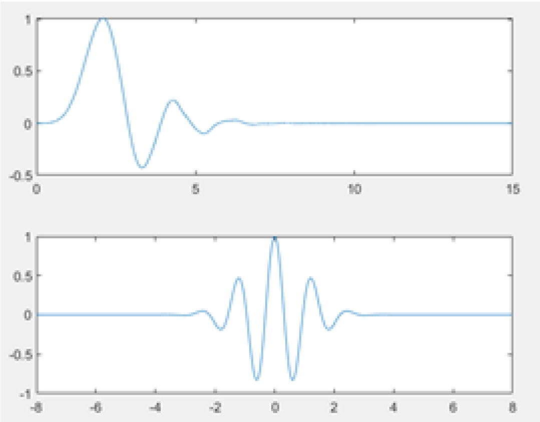



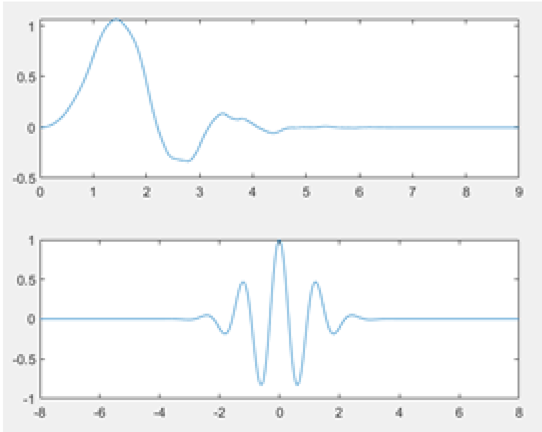




In some cases, the denoising effect of adaptive filtering has reached expectations, but there are exceptions. Adaptive filtering has a better effect on noise processing in intervals and segments, but there is distortion when the R wave changes drastically and completes a rise and fall in a short time. Considering that the processing of ECG signals is widely used in cases of abnormal arrhythmia, the original waveforms should be retained as much as possible for diagnosis. Therefore, adaptive filtering is suitable for signals that do not change drastically.

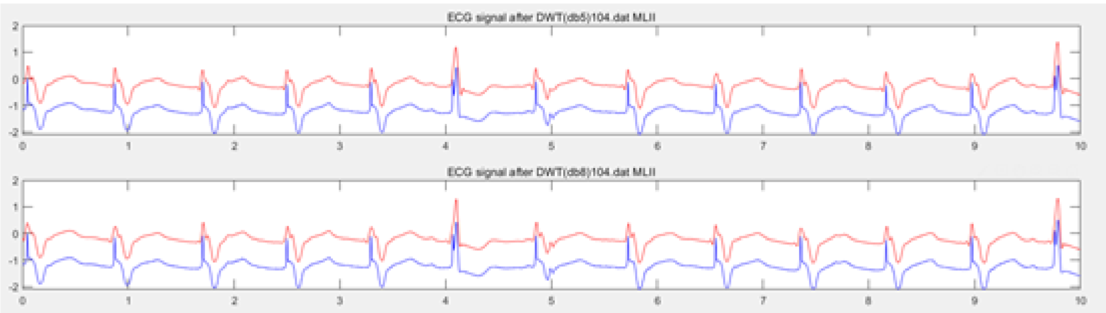
### Wavelet transform

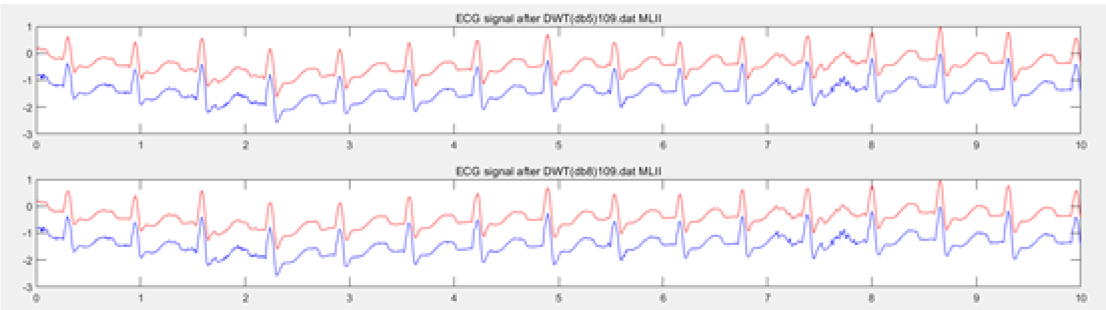
Use db5 and db8 wavelet basis functions respectively. The following figure is the scale function and wavelet function of db5 and db8.

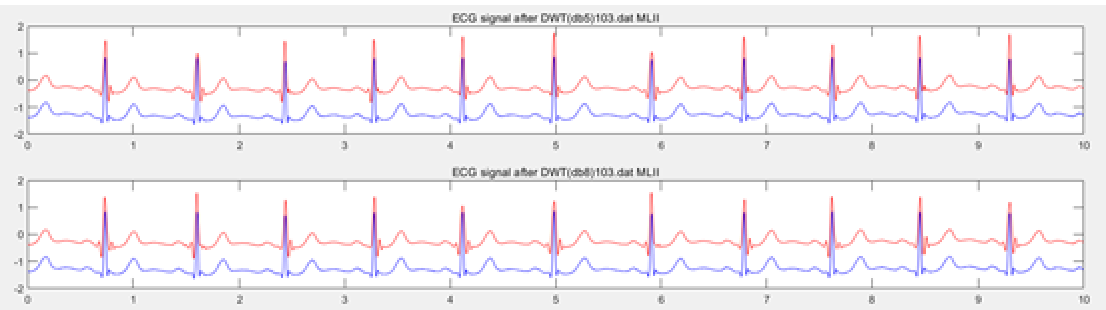




The results are shown as follows:



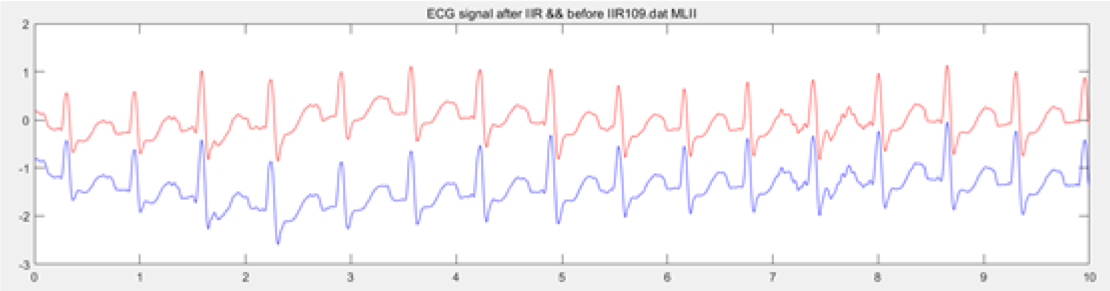




Wavelet transform retains the information of the original electrocardiogram more completely, but the denoising effect is not as stable as the previous method, especially for the details of the original signal.

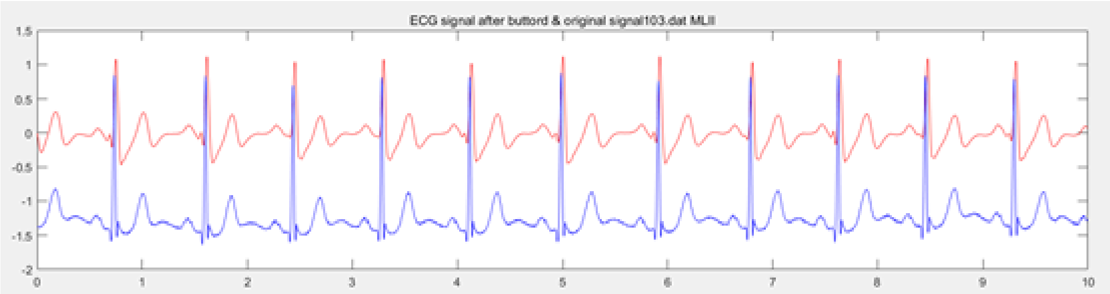
## Step 2 Baseline Wandering

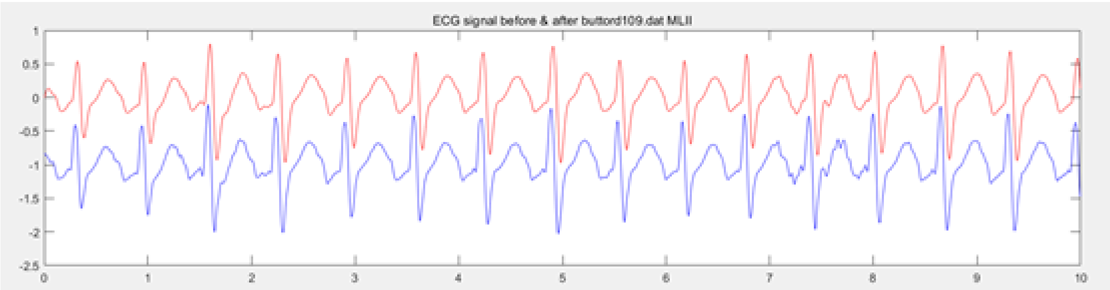
After processing the signal with base wandering using an IIR, each period of the signal is roughly maintained on the same horizontal line. The IIR filter has a good effect on the removal of baseline wandering.




## Step 3 Electromyographic Noise

The Butterworth low-pass filter attenuates the high-frequency signal, so that the high-frequency EMG interference of the input signal is removed, and the jagged curve becomes smooth in the time domain diagram.

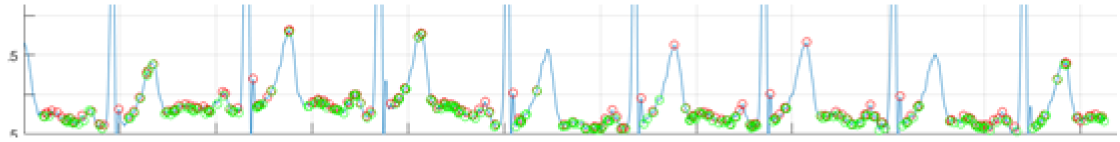



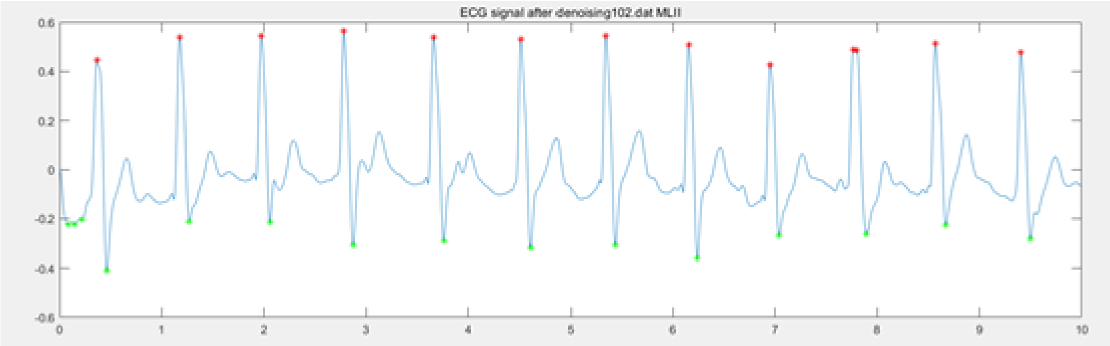

## Step 4 Peak Detection Results

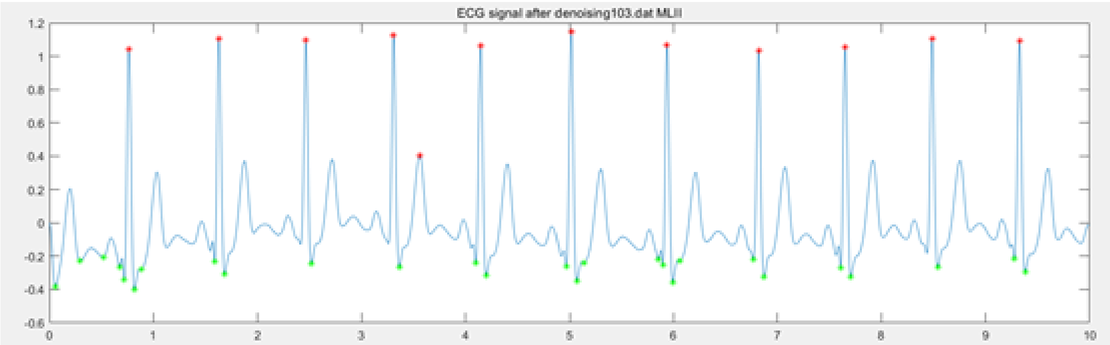
Compared with the original ECG signal, the denoised signal has a clearer identification of peaks and troughs, and the peak as well as trough interval caused by noise is very small and the amplitude is close. However, there is still a problem that the distance between peaks and troughs are very close, which could cause recognition errors.

```
[MaxV,MaxL]=findpeaks(signal_2,TIME,'minpeakheight',0.4);

Msignal=-signal_2;

[MinV,MinL]=findpeaks(nm,TIME,'minpeakheight',0.2);
```



before signal processing




after signal processing

# Conclusion

Because of the irregularity and randomness of the ECG signal itself, it is necessary to combine medical knowledge analysis to determine the position of several wave components in the basic signal.

# Reference

Moody GB, Mark RG. The impact of the MIT-BIH Arrhythmia Database. *IEEE Eng in Med and Biol* 20(3):45-50 (May-June 2001). (PMID: 11446209)

Goldberger AL, Amaral LAN, Glass L, Hausdorff JM, Ivanov PCh, Mark RG, Mietus JE, Moody GB, Peng C-K, Stanley HE. PhysioBank, PhysioToolkit, and PhysioNet: Components of a New Research Resource for Complex Physiologic Signals. *Circulation* **101**(23):e215-e220 [Circulation Electronic Pages; http://circ.ahajournals.org/content/101/23/e215.full]; 2000 (June 13).

rddata.m(Author: Robert Tratnig).

https://en.wikipedia.org/wiki/Discrete_wavelet_transform

# Terms

cardiovascular diseases

Baseline wandering (BW)

suppressed noise

removal of noise

ECG signal acquisition analog hardware

as it changes over time during a cardiac cycle