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Analysis of Butterworth Filter For Electrocardiogram De-Noising Using Daubechies Wavelets

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Abstract

Electrocardiogram (ECG) examination has been identified as an important investigation in medical diagnosis and therapy of cardiovascular diseases. However, wrong interpretation of these signals may lead to wrong diagnosis and wrong medication that can worsen the patient's situation; this is caused by noise in the signals. So denoising becomes paramount to the Physicians for better diagnosis. In this study, an extensive analysis of the Butterworth filter for ECG denoising using the Daubechies wavelets was carried out using MATLAB version 2015a. Noisy ECG signals downloaded from physionet.org under MIT-BIH arrhythmia database were de-noised using Butterworth filter displayed in both time and frequency domains while a quantitative evaluation was carried out to check the performance of the filter under signal-to-noise ratio (SNR), mean square error (MSE), and signal-to-interference ratio (SIR). Results show that denoising using Butterworth filter for SNR, MSE, and SIR gives an average value of 1.63dB, 0.2036, and 0.259dB, respectively. This implies that the Butterworth filter in ECG denoising is poor in taking care of background noise, and it also allows co-channel interference. Even though it tends to maintain a good fit for the useful signal, it also creates image signals that are also noise and cannot be recommended for ECG signal denoising. Hospitals management and cardiac health centers must understand the importance of these parameters to select ECG denoising filters for optimum diagnosis and therapy.

Keywords — *Electrocardiogram, Daubechies Wavelets, Butterworth Filter, De-Noising, Signals, noise interference.*

I. INTRODUCTION

Electrocardiogram (ECG) is amongst the frequently used procedures in medicine for diagnosis of the heart. It entails the methodology for recording the electrical movement of the heart over time, utilizing electrodes set on the skin [1], [2], [3], which is commonly used to checkmate causes of chest pain and abnormal heart rhythm. Little electrical transforms on the skin arise because of those heart muscle movements detected by electrodes then displayed on the screen. These displayed signals are made up of various wave sections, including the p wave section, QRS wave complex, and the T wave section, as seen in Fig.1.

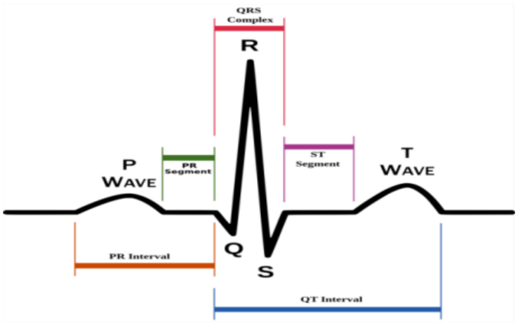

Fig.1: Single burst ECG signal [4]

A heartbeat starts with a P wave that arises due to the atria's depolarization [2]. The QRS complex represents the ventricular contraction or depolarization, which pushes the blood out of the ventricles and into the body [5], [6]. The T wave represents a ventricle's repolarization and thus marks the end of a single ECG signal. For a trained doctor, an ECG well-read and interpreted carries an extensive amount of data regarding the human heart state [7]. ECG can be the first or only indication of a possible cardiac disease [8]. The information that an ECG signal provides include but not limited to; Heartbeats rhythm, Heart position, and conduction disturbances, diagnose damages done to the muscle cells (of the heart), change in an electrolyte, Relative chamber size, Effects of drugs on the heart condition, Change in electrolyte concentration [2], [9].

Working with signals obtained for research on Electrocardiogram often comes with noise [10]. This noise exists in the low or high amount due to many factors, which affects the genuine nature of obtained results from the use of such data, which can lead to wrong interpretation and wrong medication thereof. The various types of noise can be combined into three kinds, including baseline wander, power line interference (50/60 Hz), and Electromyography

Noise (EMG) [11]. For this reason, it is paramount that denoising techniques are employed to minimize the dangers posed by this noise in order to get a near-perfect result [12]. ECG de-noised interpretation is therefore of great importance in managing a patient's health [13], [14]. This skill is so important that all clinicians who make clinical assessments using ECG need to master it [15]. De-noising is the act of extracting unwanted signals (noise) from actual or required data for clean and accurate diagnosis. Recording of ECG signals is usually accompanied by noise, also known as artifacts. This can be by baseline wandering due to muscle contraction or patient's movement, Power Line Interference (PLI) [16]. For correct diagnosis of the heart, removing this noise is necessary; else, there would be misinformation about the disease.

Wavelets are mini waves that exist for a finite duration, unlike sinusoids. There are various types of wavelets such as Harr, Symmelets, but Daubechies wavelets and specifically db4 were chosen for this research because of their close similarity to ECG in terms of tracings and its property of a maximum number of vanishing moments [16]. Extensive research has been carried out from a wide sense of perspectives and approach, and it is practically impossible to account for all of them [5], [16]. Some of the various methods of ECG denoising includes; method of suggested signal to noise residue algorithm dependent on wavelet principle [17], application of digital filter elaborated on ECG noise cancelation [18], Infinite Impulse Filter (IIR), notch filter with transient suppression in ECG [19], classical method in high pass filter for removal of a very low-frequency component of ECG recordings [20], linear filtering in eliminating baseline wander within the frequency range of 0.5Hz [21], analysis of Butterworth and Chebyshev filters for ECG denoising utilizing wavelets [16], and stationary wavelet transform method is also known as dyadic wavelet transform [22]. For this study's purpose, an analysis of the Butterworth filter for ECG denoising was carried out. This research will help all hospital health organizations that carry out ECG examinations for better and improve diagnosis for patient therapy and treatment.

II. LITERATURE REVIEW

A. Butterworth Filter

Butterworth filter is a form of high order filter designed to have a very flat response (i.e., no ripples) in the passband [23], [16] and steep slope immediately after the cut-off. Fig. 2 shows the gain or frequency response as obtained via discrete-time Butterworth filter. In order to achieve this, [24] proposed a filter design with a possible gain or frequency response which is defined as follows:

$$G(\omega) = \frac{1}{\sqrt{1+\varepsilon^2(\frac{w}{w_c})^{2n}}} \qquad (1)$$

where,

ω = Angular frequency (rad^{-s})

n = Number of poles in the filter, which is the same as the amount of reactive elements of a passive filter

ε = Maximum passband gain

ω_c = Cut-off frequency

G = Transfer function

When ε = 1 and in a more linear form, Equation (1) can be re-written as:

$$\frac{V_{out}}{V_{in}} = \frac{1}{\sqrt{1+(\frac{f}{f_c})^{2n}}} \qquad (2)$$

where,

f = frequency at which calculation is made

f_c = The cut-off frequency usually half power or -3dB.

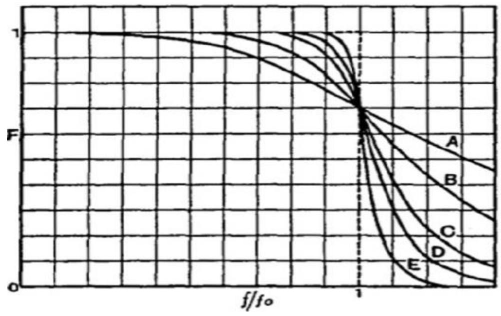

Fig. 2: Butterworth filter frequency response plot [24]

Butterworth [24] created higher order filters from bipolar filters, which are kept separate by a vacuum tube amplifier. The letters from A to E in his graph, as seen in Fig. 2, represent the frequency response of 2, 4, 6, 8, and 10-pole filters.

III. MATERIALS AND METHOD

A. Materials

The materials and their specifications used for this research include a windows 10 laptop with a 1.6Hz processor, 3.85 usable Ram, 64-bit operating system, MATLAB version 2015a, and noisy ECG signal obtained from physionet.org under MIT-BIH arrhythmia database.

B. Method

The method involved is in two stages, which includes signal denoising and performance analysis.

a) Signal De-Noising Method:

The method involved in this research was carried out according to the following steps:

- Download the noisy signal from physionet.org, which is in the time domain.

- Convert to wavelet (Frequency) domain using MATLAB software.
- De-noise the signal with the Butterworth filter using Daubechies wavelets.
- Convert the de-noised signal back to the time domain

b) Performance Analysis Method:

To check the performance of the filter, various analyses were carried out, which includes the calculation of Signal to Noise Ratio (SNR), Mean Square Error (MSE), and Signal to Interference Ratio (SIR).

Signal to Noise Ratio (SNR): The signal-to-noise ratio (SNR) compares the desired signal level to the level of background noise. Sources of noise can include microwave ovens, cordless phones, Bluetooth devices, wireless video cameras, wireless game controllers, fluorescent lights, and more [25]. The noise does not include co-channel interference from other radio transmitters. According to [25], a 10-15dB ratio is the accepted minimum to establish an unreliable connection; 16-24dB is usually considered poor; 25-40dB is good, and a ratio of 41dB or higher is considered excellent. The SNR value can be calculated using the following equations:

$$SNR_{dB} = 10 \log_{10}\left(\frac{S}{N}\right)_P \quad (3)$$

Or,

$$SNR_{dB} = 20 \log_{10}\left(\frac{S}{N}\right)_v \quad (4)$$

where,
S = RMS power of ECG signal
N = RMS power of the de-noised ECG signal

Mean Square Error (MSE): The mean square error (MSE) measures the average of the errors' squares, that is, the average square difference between the estimated value and the actual value. It measures how close-fitted the line is to the data point and provides us with confidence that our assumptions about the data trends are correct. The smaller the MSE value, the better the fit, as smaller values imply smaller error magnitudes [26]. The MSE value was calculated using the following Equation:

$$MSE = \frac{\sum(s - \hat{s})^2}{N} \quad (5)$$

where,
s = Noisy signal
$\hat{s}$ = De-noised signal
N = Number of samples

Signal to Interference Ratio (SIR): The signal to interference ratio (SIR) is similar to SNR, but here the interference is specific to co-channel interference from other radio transmitters. According to [27], the higher the SIR, the minimal the interference, and the SIR must reach a minimum threshold for the signals to be detected. Suksompong [28] explained that SIR should be greater than a specified threshold for proper signal operation. In the 1G AMPS system, designed for voice calls, the threshold for acceptable voice quality is SIR equal to 18dB, for the 2G digital AMPS system (D-AMPS or IS-54/136), a threshold of 14 dB is deemed suitable, and for the GSM system, a range of 7–12 dB, depending on the study done, is suggested as the appropriate threshold, While, the probability of error in a digital system depends on the choice of this threshold as well. Wireless devices work reliably with a SIR value of 0dBm or less [29]. The SIR value was calculated using the following Equation:

$$SIR = \sum_{i=1}^{n}\left[\frac{y_{i(input\ signal)}}{y_{i(noise)}}\right] \quad (6)$$

where,
$y_{i(input\ signal)}$ = Amplitude of input (Noisy signal)
$y_{i(noise)}$ = Amplitude of noise removed through filtering.

IV. RESULTS

A. ECG De-Noising Simulation Results

The simulation results for the ECG denoising of different signals (104, 108, 109, 113, 117, 119, 209, 222, 230, and 232) have been carried out using the Butterworth filter. The process uses equations 1 and 2 to carry out the simulation, and the results are obtained in both time and frequency domain representation. However, since the researcher cannot present all the simulated results, two signals (108, 109) de-noised were randomly selected and presented both in their time and frequency domains, as shown in Figures (3, 4, 5, and 6).

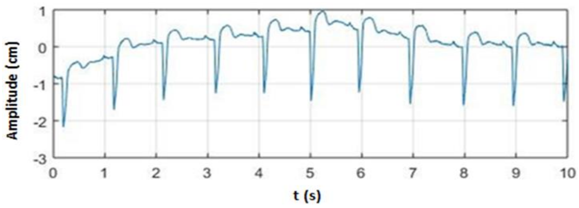

Fig. 3a: Noisy signal in the time domain (signal 108)

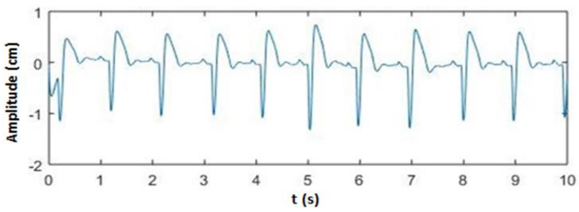

Fig. 3b: De-noised signal in the time domain (signal 108)

For signal 108, Fig. 3a shows the noisy signal 108 represented in its time domain. 3b is a representation of de-noised signal 108 using the Butterworth filter in its time domain. Comparing Figs. 3a and 3b, we see that the de-noised signal in Fig. 3b is sharper and clearer, but its original shape is not preserved.

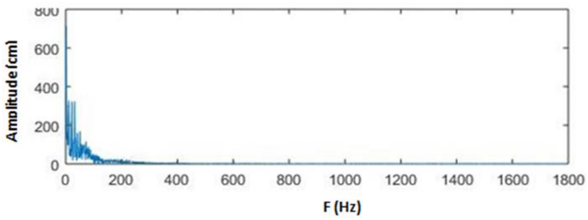

Fig. 4a: Noisy signal in the frequency domain (signal 108)

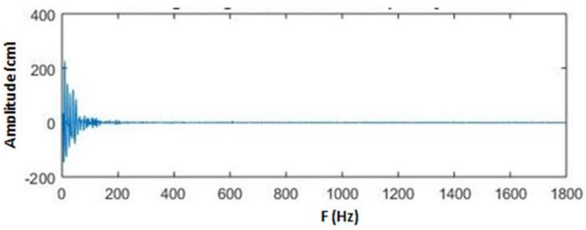

Fig. 4b: De-noised signal in the frequency domain (signal 108)

Fig. 4a is the noisy signal 108 represented in its frequency domain, while Fig. 4b is a representation of de-noised signal 108 using the Butterworth filter in its frequency domain. Comparing Figs. 4a and 4b, we observe that the de-noised signal in Fig. 4b is sharper and clearer but produces an image signal along the negative axis, which implies a porous effect. Such an effect may not be good for an ECG denoising filter.

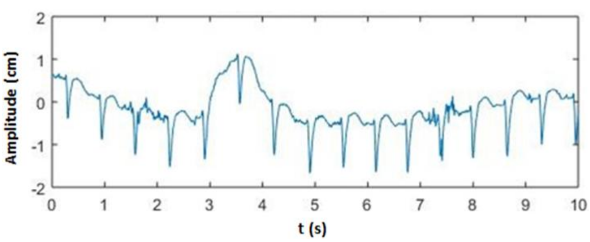

Fig. 5a: Noisy signal in the time domain (signal 109)

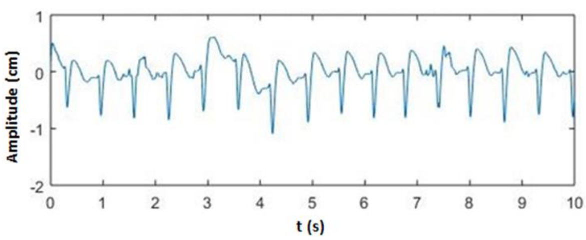

Fig. 5b: De-noised signal in the time domain (signal 109)

Similarly, for signal 109, Fig. 5a shows the noisy signal 109 represented in its time domain. 5b is a representation of de-noised signal 108 using the Butterworth filter in its time domain. Comparing Figs. 5a and 5b, we observe that the de-noised signal in Fig. 5b is sharper and clearer and did not maintain the original shape.

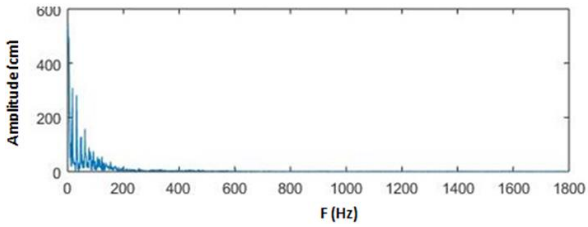

Fig. 6a: Noisy signal in the frequency domain (signal 109)

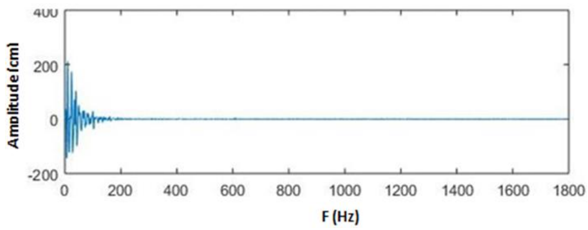

Fig. 6b: De-noised signal in the frequency domain (signal 109)

Fig. 6a is the noisy signal 109 represented in its frequency domain, while Fig. 6b is the de-noised signal 109 using the Butterworth filter represented in its frequency domain. Again comparing Figs. 6a and 6b we observe that the de-noised signal in Fig. 6b, even though sharper and clearer, could not preserve the signal's shape but produce an image signal in the negative axis, confirming that the Butterworth filter may not be a good filter for ECG signal denoising. This is because the interpretation of ECG depends on the signal shape and orientation; any change in the signal's orientation may lead to wrong diagnoses.

B. Performance Analysis

The ECG signal's performance analysis denoises the different sampled ECG signals (104, 108, 109, 113, 117, 119, 209, 222, 230, and 232) using the Butterworth filter has been carried out. The analysis for SNR, MSE, and SIR was carried out using equations 3 to 6 and presented in Table 1.

Table 1 presents the result of the performance analysis of the Butterworth filter for ECG denoising. From Table 1, it can be observed that the SNR for the ten (10) sampled ECG signals de-noised using Butterworth filter varies from 0.20dB to 4.17dB with a mean value of approximately 1.63dB, while the MSE varies from 0.0118 to 0.78279 with a mean value of approximately 0.2036, and the SIR varies from -3.738dB to 1.887dB with a mean value of approximately 0.259dB.

V. DISCUSSION

The graphical representation of the signals shows that the signal has been de-noised, as evident from the de-noised signals' lightness compared to its corresponding original signals, which are darker. However, though it is a digital signal, the Butterworth filter still falls under examples of IIR filters that generally do not have peak preserving properties, as evident in the de-noised signals. Besides, the filter tends to create image signals in the negative axis when represented in the frequency domain. This could also be a form of noise

The performance analysis findings have revealed that the average SNR value after denoising with the Butterworth filter is approximately 1.63dB. According to [25], a 10-15dB ratio is the accepted minimum but unreliable; 1.63 dB is way below this value, indicating a very poor performance of the filter. Therefore, the signal produced along the negative axis when the de-noised signal is represented in the frequency domain could be the signal's noisy component represented as an image signal. This implies that the Butterworth filter is not a good filter for ECG denoising. This finding is similar to the work of [30], [3], and [2], but not in line with the works of [31] that obtain 27.32dB using Butterworth filter and [32] that obtained an average value of 19.64dB which is also poor but better than the Butterworth filter as they had used a method of suppressing the Fourier coefficient corresponding to the noise band.

From the analysis of MSE, findings have revealed an average value is 0.2036, which is good. This shows how close-fitted our de-noised signal line is to the data point. According to [26], smaller values imply smaller magnitudes of error; it provides us with confidence that our assumptions about trends in the data are correct. This is in line with the findings of [2] that obtained 0.1201 for the S-G filter and 0.0135 for DWT.

Finally, from the analysis of SIR, findings have revealed an average value of approximately 0.259dB. According to [27], the higher the SIR, the minimal the interference. Since the threshold value is 18dB, a SIR value of 0.259dB is very low and unreliable. This implies that the Butterworth filter allows co-channel interference from other radio transmitters while carrying out denoising. This finding is similar to that of [16] that obtain a SIR value of 1.003dB using the Butterworth filter.

VI. CONCLUSIONS

De-noising of ECG signals is very important in medical diagnosis. It helps to maintain the quality of the signal for good diagnosis and patient therapy, leading to easy detection of a common disease that can help reduce the death rate due to cardiovascular problems. The use of filters in ECG signal denoising has proven to be one solution for good and effective ECG signals. The higher the SNR and SIR value of a filter, the better its performance, while the lower the MSE values of a filter towards zero (0), the better fitted is the signal to the user data.

TABLE I
SNR, MSE and SIR values for ECG signal de-noising using Butterworth filter

S/NO	ECG SIGNAL	SNR (dB)	MSE	SIR (dB)
1	104	4.167281	0.029363	1.887332
2	108	2.772084	0.135608	-3.738311
3	109	1.591261	0.176809	-1.846677
4	113	0.201191	0.076766	0.980739
5	117	0.260447	0.723611	0.707065
6	119	0.860306	0.782789	1.162270
7	209	0.672459	0.011753	1.107870
8	222	0.860959	0.031407	0.866190
9	130	3.173209	0.038855	0.363691
10	232	1.772571	0.028811	1.100660
	Mean	1.633177	0.203577	0.259083

However, this study has found that the Butterworth filter in ECG denoising is very poor in taking care of the background/internal noise, and it also allows co-channel interference from other transmitters. Even though it tends to maintain a good fit for the useful signal, it can create an image signal, which is also noise and could affect the interpretation of the ECG signals. These properties make it a poor filter for ECG denoising as such cannot be recommended. Management of hospitals and cardiac health centers must understand the importance of SNR, MES, and SIR values in selecting denoising filters, so that while de-noising an ECG signal, the quality of the signal can be maintained for a good diagnosis and treatment of the cardiac patients.

For further works, it is recommended that analysis that could compare two or more filters be done; so that the best performance filter in terms of all the parameters analyzed can be identified for a good and excellent ECG denoising for better diagnosis and therapy.

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