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Analysis of Savitzky-Golay Filter for Electrocardiogram De-Noising Using Daubechies Wavelets

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Abstract

Electrocardiogram (ECG) examination is of great importance in medical diagnosis of the cardiac disease, but wrong interpretation due to noise interference in the signal could be dangerous as this may lead to wrong diagnoses of patient's heart condition. De-noising helps to reduce the noise level for a better interpretation of the signals. In this study, an analysis of Savitzky-Golay (S-G) filter for ECG de-noising using Daubechies wavelets has been carried out using MATLAB version 2015a. Noisy ECG signals downloaded from physionet.org under MIT-BIH arrhythmia database was de-noised using S-G filter of polynomial order 9 to data frames of length 21 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 de-noising using S-G filter for SNR, MSE, and SIR gives an average value of 32.78dB, 0.0001 and 1852.358dB respectively. This implies that the S-G filter helps eliminates the background noise as well as maintaining a good fit for our data, and also do not allow co-channel interference from other radio transmitters, which makes it an excellent filter for ECG signal de-noising. Hospitals management and cardiac health centers most understand the importance of these parameters in the selection of de-noising filters for good quality ECG in diagnosis and treatment of cardiac patients.

Keywords: Electrocardiogram (ECG); Savitzky-Golay Filter; Daubechies Wavelets; De-Noising; Signal to Noise Ratio (SNR); Signal to Interference Ratio

INTRODUCTION

An Electrocardiogram (ECG) is a non-invasive test used in determining the regular rhythmic activities of heart condition [1, 2, 3], it is a bio electric signal used to account for the electrical activities of the heart [4]. This test is done over time and helps in the study and understanding of cardiac disease [2]. Noise interference in ECG signal is inevitable, because when recording and ECG signal it is always accompanied with some level of noise which can only be minimized to a barest and interpretable minimum [5]. According to [5] the ECG signal carries information about the structure and function of the heart which normally has a dynamic range of 0.05–100 Hz and 1–10 mV. This noise comes in different frequencies, low or high due to different factors. The ECG signal is pictured by five peaks and valleys labeled by the letters P, Q, R, S, T [6, 7]. Also, there is sometimes a 'U' wave in ECG signal which is characterized with having very low amplitude, more often than not is absent [7]. An ECG tracing as shown in Fig. 1 comprises of a repeating cycle of three electrical sections [7]. The P wave arises due to the depolarization of the atria, the QRS complex represents the ventricular contraction or depolarization which pushes the blood out of the ventricles and into the body and the T wave represents the re-polarization of ventricle and thus marks the end of a single ECG signal [8, 9, 10, 11, 12].

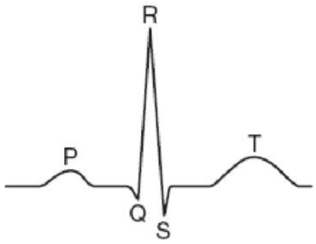

Fig. 1 Single burst ECG signal

According to Velayudhan and Peter [7] during ECG signal acquisition and transmission, it is affected by various noise; mainly two types are present. The one with high frequency which includes Electromyogram noise, Additive white Gaussian noise (AWGN) and power line interference. While the other type, baseline wandering is a low frequency noise. The noises contaminated in the ECG signal may lead to wrong interpretation. ECG can be the first or only indication of a potential cardiac disease [12, 13]. ECG signals de-noised interpretation is of great importance in caring for a patient's health [14].

De-noising is the act of extracting unwanted signal (noise) from actual or required data for clean and accurate diagnosis [15]. Different de-noising techniques are available in the literature as various types of filters have been used for filtering ECG signals, traditional methods such as linear filtering, signal averaging and their various combinations [2]. For the sake of this research work, an analysis of Savitzky-Golay (S-G) filter has been carried out as a technique for de-noising of ECG signal using Daubechies wavelet with the help of a MATLAB version 2015a. This research will be beneficial to all hospitals and health organizations that carry out ECG examination as better filtering of the signal would minimize the situation of repeating ECG tracings due to presence of noise which wastes time. Also, it would save the patient the uncomfortable situation of going bare-chested (especially the ladies) for another ECG tracing. While in the long run, the government benefits in a case of a government owned hospital, because not more than one set of material would be used for a patient thereby maximizing the total overhead cost of management.

LITERATURE REVIEW

Savitzky-Golay (S-G) Filters

In 1964, Savitzky and Golay proposed a way of retaining the original signal shape, and thus, its information while still using the principles of moving average filters [16]. Moving average filter is one of the simplest and most straightforward ways of filtering a noisy signal [9]. The generalized formulae of the repeated process of averaging in order to filter this signal is as shown in Eqn. 1.

$$g_k = \sum_{i=k-m}^{k+m} C_i X_k \tag{1}$$

Where;

C_i =Filters coefficient with constant value $1/n$
X_k =A random point of a discrete data set
m =Static number

In order to do so, they sought to replace C_i in Eqn. 1 with polynomials of higher order. To do this, they proposed an approximation of local least-square polynomial [17] fitting the polynomial line to the $'n'$ points within the window. The criteria used in choosing the filtered value g_k is by considering the value which best retain the fundamental shape of the data; the coefficient of each polynomial must be determined so that the equivalent polynomial curve best matches the data provided [18, 19].

Mathematically, the idea is to find the best mean-square fit of a polynomial of say, degree p via a set of $2m+1$ consecutive values, where $p < 2m+1$. This according to [9] is of the form:

$$g_k = \sum_{i=0}^{i=p} b_{pi}\, k^i = b_{p0} + b_{p1}k + b_{p2}k^2 + \cdots + b_{pi}k^p \qquad (2)$$

Taking the first and second order derivatives of Eqn. 2 we have:

$$\frac{d_g k}{dk} = b_{p1} + 2b_{p2}k + 3b_{p3}k^2 + \cdots + pb_{pp}k^{p-1} \qquad (3)$$

$$\frac{d_g K}{dk^2} = 2b_{p2} + 6b_{p3}k + \cdots + (p-1)pb_{pp}k^{p-2} \qquad (4)$$

Generally written;

$$\frac{d_g^p K}{dk^p} = p^b{}_{pp} \qquad (5)$$

By the least squares criteria, it is required to minimize the sum of the squares of the difference the observed values $y_k$and estimate values inside the window, thus;

$$\frac{\partial}{\partial b_{pi}}\left[\sum_{k=-m}^{k=m}(g_k - y_k)^2\right] = 0 \qquad (6)$$

Expressing Eqn. 6 with respect to b_{pk} gives:

$$\frac{\partial}{\partial b_{pk}}\left[\sum_{k=-m}^{k=m}\left(b_{p0} + b_{p1}k + \cdots + b_{pp}k^p - y_k\right)^2\right]$$
$$= 2\sum_{k=-m}^{k=m}\left(b_{p0} + b_{p1}k + \cdots + b_{pp}k^p - y_k\right)k = 0 \qquad (7)$$

Conclusively, S-G filter has an important peak preserving property which is very useful in ECG signal analysis [20].

MATERIALS AND METHODS

Materials

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

Method

Signal De-Noising Method

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

i. Download the noisy signal from physionet.org which is in time domain.
ii. Convert to wavelet (Frequency) domain using MATLAB software.
iii. De-noise the signal with the S-G filter using Daubechies wavelets.
iv. Convert the de-noised signal back to time domain

Performance Analysis Method

To check the performance of the filter various analysis 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 level of desired signal to the level of background noise. Sources of noise can include microwave ovens, cordless phone, Bluetooth devices, wireless video cameras, wireless game controller, fluorescent lights, and more [21]. The noise does not include co-channel interference from other radio transmitters. According to Net Spot [21], a ratio of 10-15dB 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:

$$SNR_{dB} = 10 \log_{10}(\frac{S}{N})_P \quad (8)$$

Or,

$$SNR_{dB} = 20 \log_{10}(\frac{S}{N})_v \quad (9)$$

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 squares of the errors, that is, the average square difference between the estimated value and the actual value. It measures how close fitted line is to data point and provides us with confidence that our assumptions about trends in the data are correct. The smaller the MSE value the better the fit, as smaller values imply smaller magnitudes of error [22]. The MSE value was calculated using the following equation:

$$MSE = \frac{\sum(s-\hat{s})^2}{N} \quad (10)$$

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 Nnebe, Onoh and Ohaneme [23] the higher the SIR the minimal the interference and the SIR must reach a minimum threshold for the signals to be detected. Suksompong [24] 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 SIR value of 0dBm or less [25]. The SIR value was calculated using the following equation:

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$$SIR = \sum_{i=1}^{n} [\frac{y_{i(input\ signal)}}{y_{i(noise)}}] \tag{11}$$

Where,

$y_{i(input\ signal)}$ =Amplitude of input (Noisy signal)

$y_{i(noise)}$ =Amplitude of noise removed through filtering.

RESULTS

ECG De-Noising Simulation Results

The simulation results for the ECG de-noising of different signals (104, 108, 109, 113, 117, 119, 209, 222, 230 and 232) have been carried out using S-G filter of polynomial order 9 to data frames of length 21. The process uses equations 1 to 7 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, for the purpose of presentation, the results of two signals (104, 230) de-noised were randomly selected and presented both in their time and frequency domains as shown in Figs (2, 3, 4, 5, 6, 7, 8 and 9).

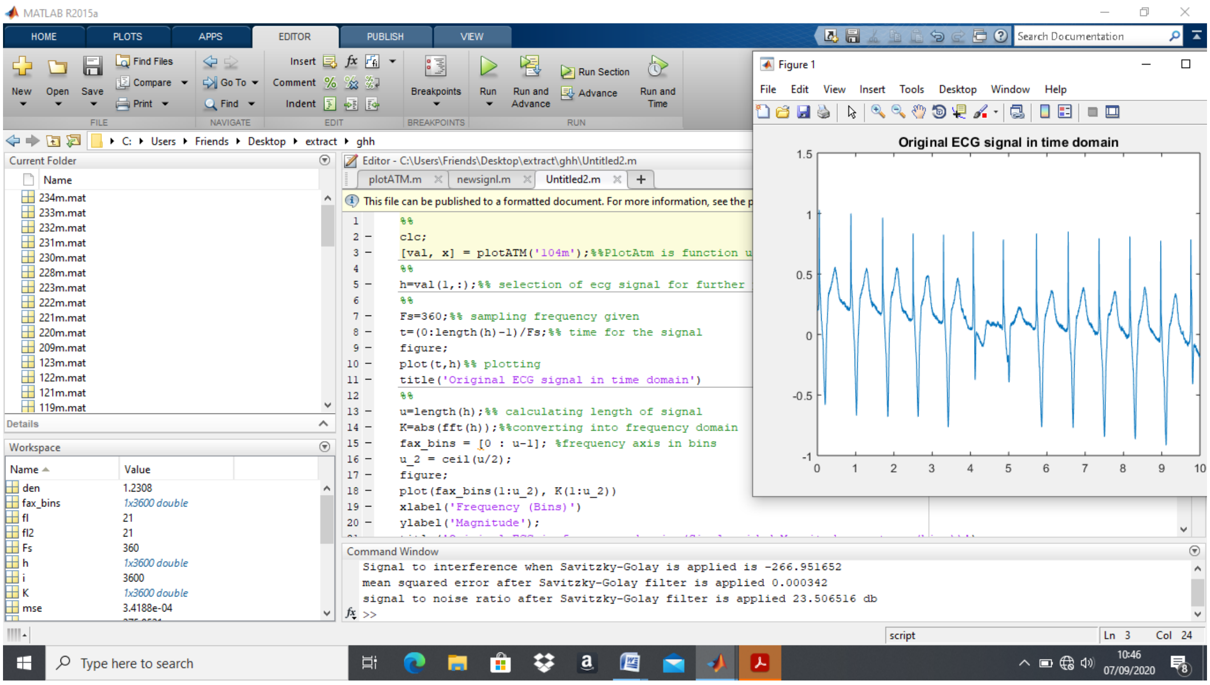

Fig. 2 Representation of noisy signal in time domain (signal 104)

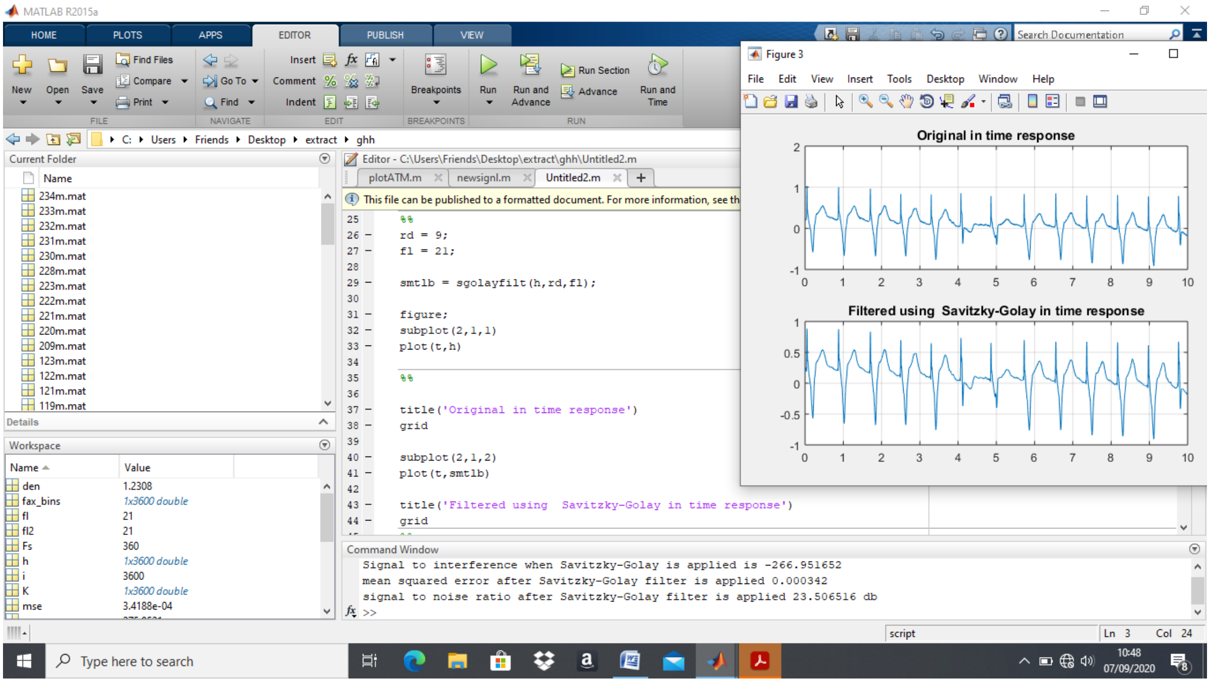

Fig. 3 De-noised signal filtered using Savitzky-Golay in time response (signal 104)

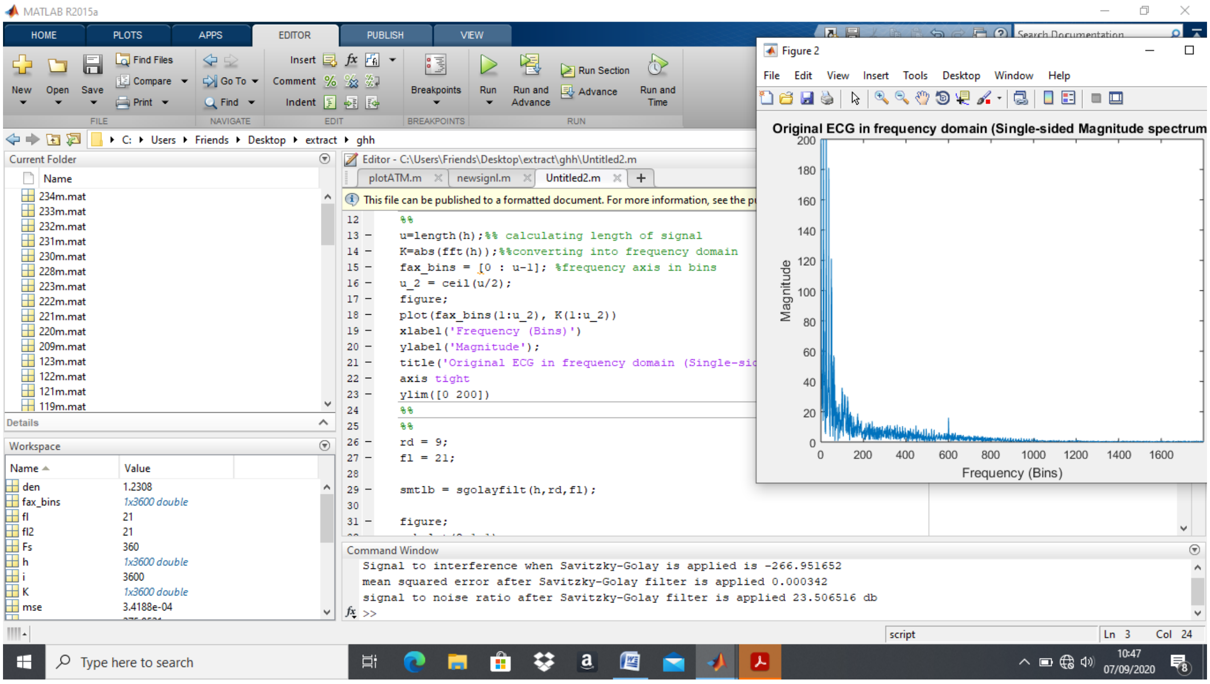

Fig. 4 Representation of noisy signal in frequency domain (signal 104)

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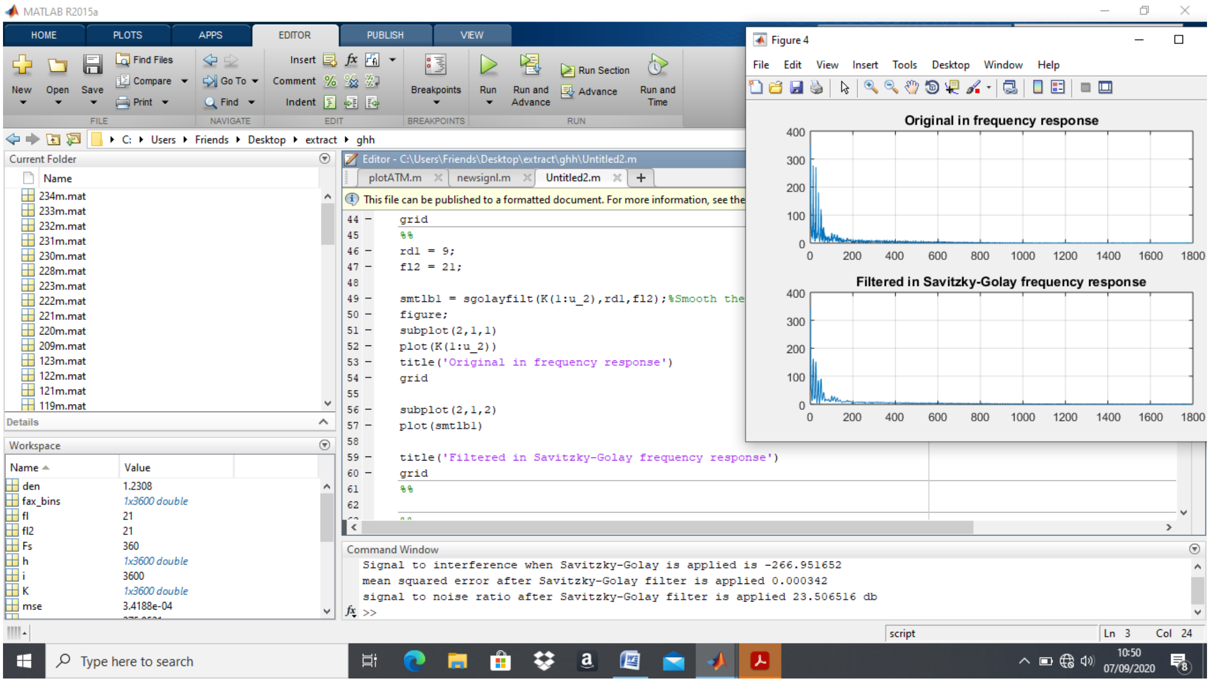

Fig. 5 De-noised signal filtered using Savitzky-Golay in frequency response (signal 104)

For signal 104, Fig. 2 shows the noisy signal 104 represented in its time domain, while Fig. 3 is a representation of de-noised signal 104 filtered using the S-G filter in its time domain. Comparing Figs. 2 and 3 we see that the de-noised signal in Fig. 3 is sharper and clearer and still maintaining its original shape, showing that only the noise component was removed. Fig. 4 is the noisy signal 104 represented in its frequency domain, while Fig. 5 is a representation of de-noised signal 104 filtered using the S-G filter in its frequency domain. Comparing Figs. 4 and 5 we observe that the de-noised signal in Fig. 5 is sharper and clearer and still maintains its original shape, though reduced in amplitude due to removal of the noise component of the signal, showing that the S-G filter is a good de-noising filter.

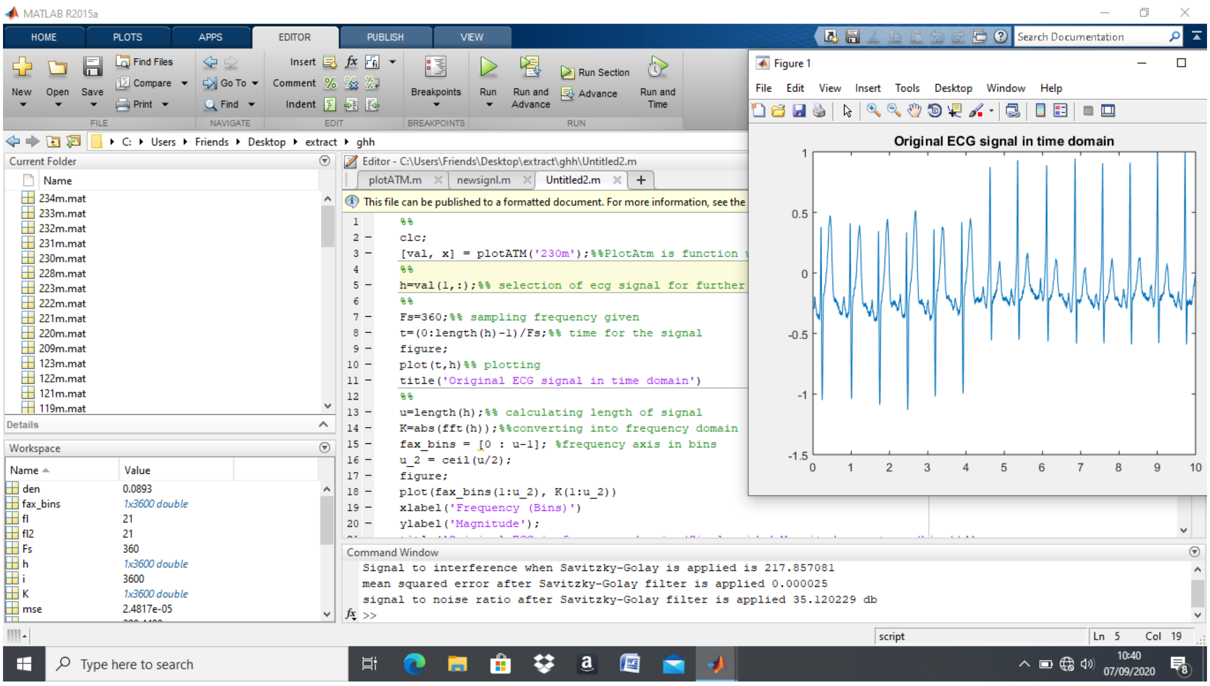

Fig. 6 Representation of noisy signal in time domain (signal 230)

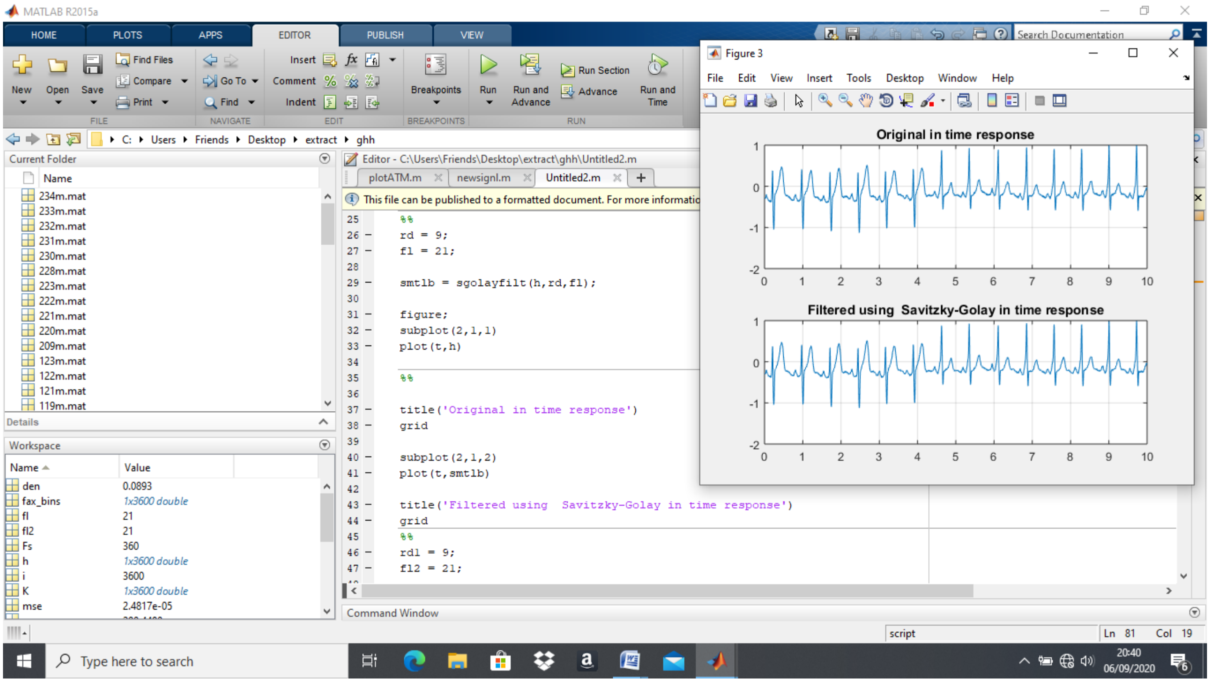

Fig. 7 De-noised signal filtered using Savitzky-Golay in time response (signal 230)

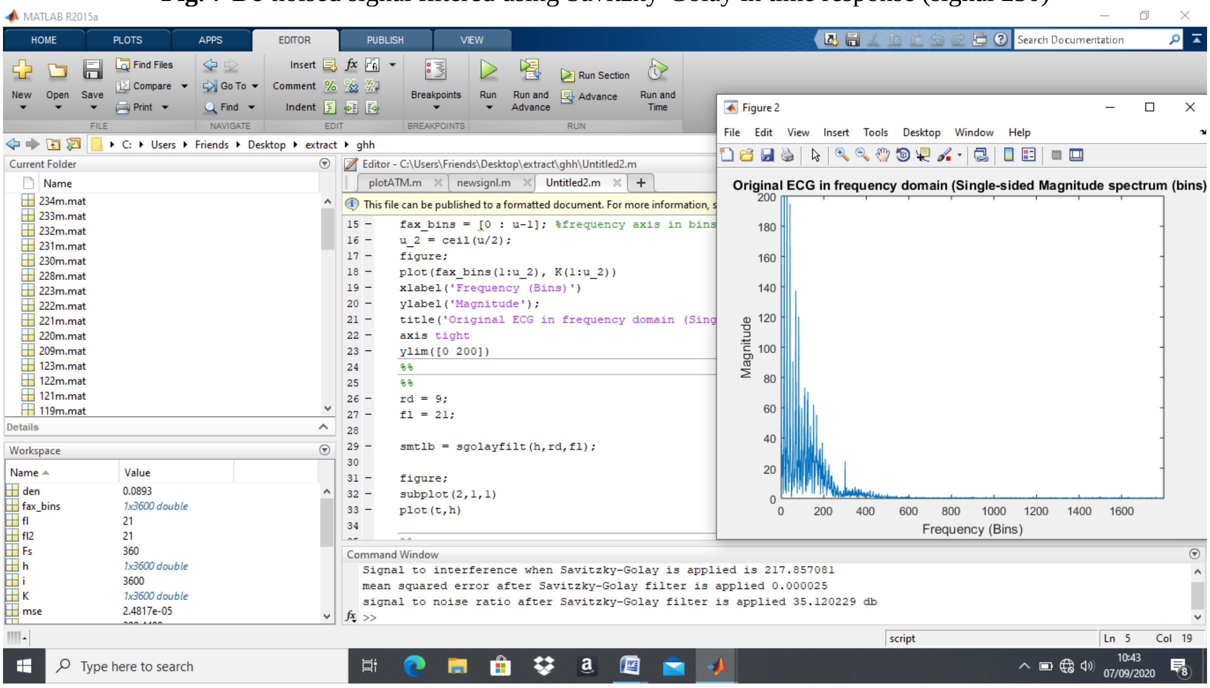

Fig. 8 Representation of noisy signal in frequency domain (signal 230)

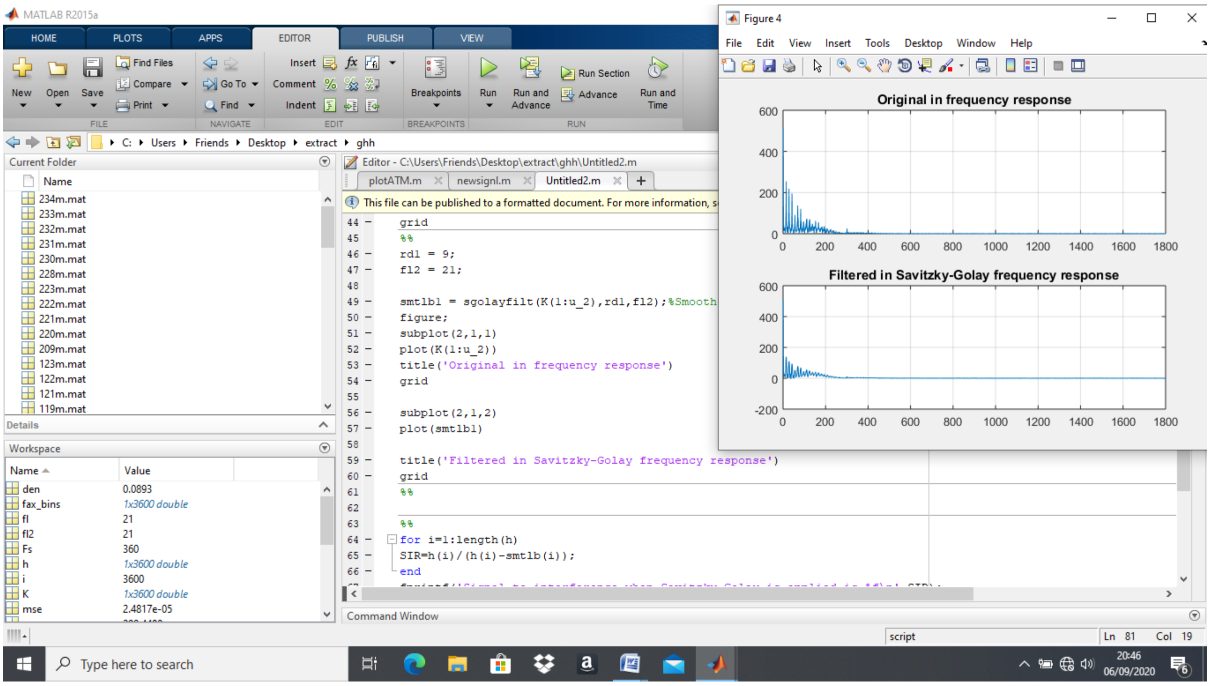

Fig. 9 De-noised signal filtered using Savitzky-Golay in frequency response (signal 230)

Similarly, for signal 230, Fig. 6 shows the noisy signal 230 represented in its time domain, while Fig. 7 is a representation of de-noised signal 230 filtered using the S-G filter in its time domain. Comparing Figs. 6 and 7 we observe that the de-noised signal in Fig. 7 is sharper and clearer and still maintaining its original shape. Fig. 8 is the noisy signal 230 represented in its frequency domain, while Fig. 9 is the de-noised signal 230 filtered using the S-G filter represented in its frequency domain. Again comparing Figs. 8 and 9 we observe that the de-noised signal in Fig. 9 is sharper and clearer and still maintains its original shape, though the amplitude of the signal is reduced due to removal of noise component of the signal, which further confirms the effectiveness of S-G filter in terms of signal de-noising.

Performance Analysis

The performance analysis for the ECG signal de-noising of the different sampled ECG signals (104, 108, 109, 113, 117, 119, 209, 222, 230 and 232) filtered using S-G filter of polynomial order 9 to data frames of length 21 has been carried out. The analysis for SNR, MSE, and SIR were carried our using equations 8 to 11. Again, since the researcher cannot present all the simulated results, the simulated results for the two signals 104, 230 were randomly selected and presented in Figs. 10 and 11 respectively. The general results for analysis of the different sampled ECG signals (104, 108, 109, 113, 117, 119, 209, 222, 230 and 232) on SNR, MSE, and SIR are presented as shown in Table 1.

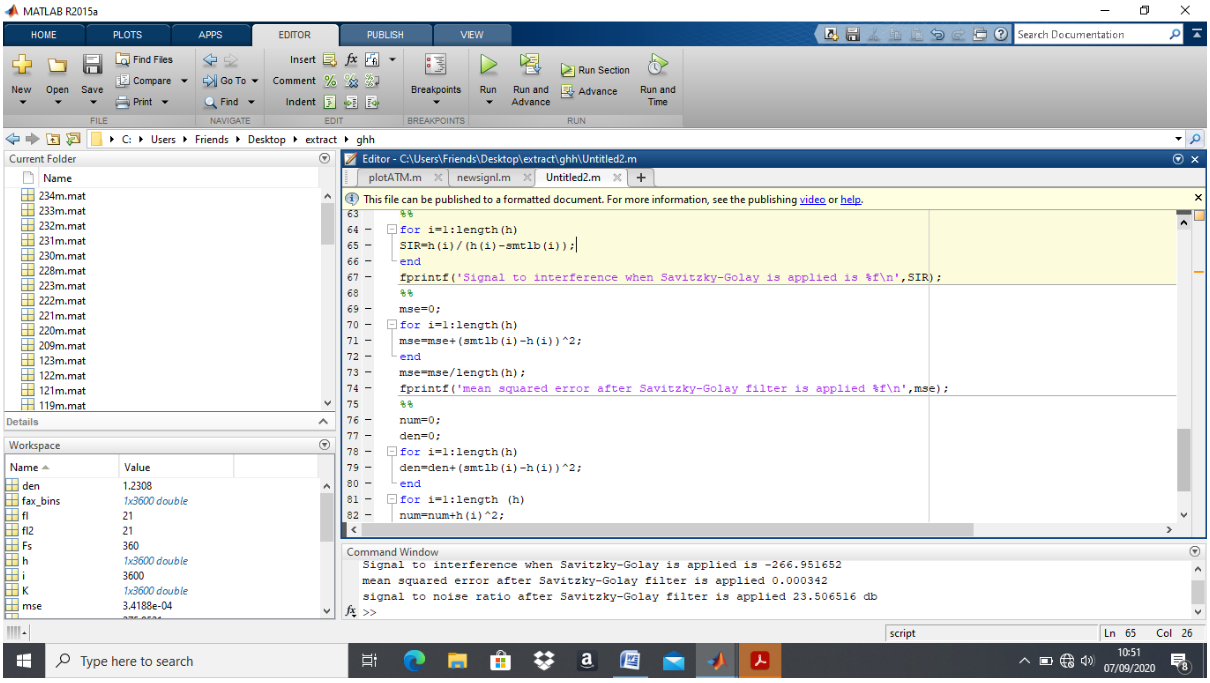

Fig. 10 S-G filtering result for SNR, MSE and SIR for (signal 104)

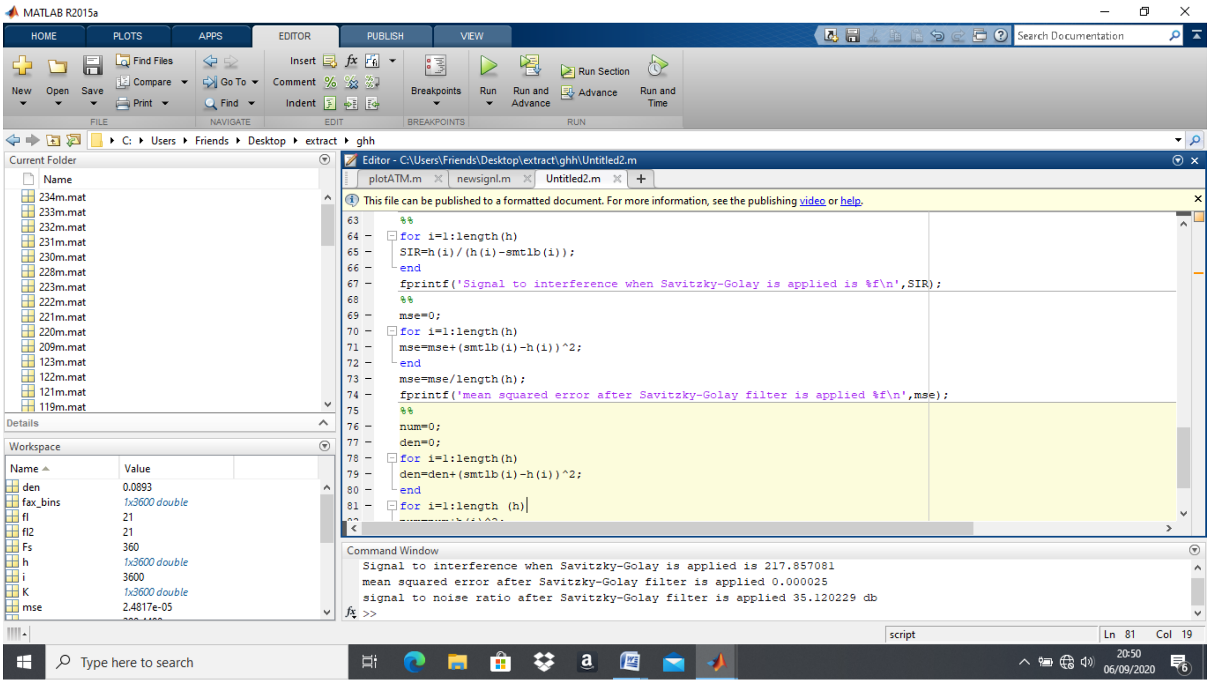

Fig. 11 S-G filtering result for SNR, MSE and SIR (signal 230)

Table 1 SNR, MSE and SIR values for ECG signal de-noising using S-G filter

S/NO	ECG SIGNAL	SNR (dB)	MSE	SIR (dB)
1	104	23.506516	0.000342	-266.951652
2	108	36.051186	0.000064	-222.594120
3	109	35.516700	0.000072	3647.437893
4	113	31.530670	0.000057	609.196198
5	117	42.452362	0.000044	8159.417477
6	119	42.804288	0.000050	1092.976430
7	209	22.170155	0.000083	-299.202217
8	222	26.506191	0.000086	22.577369
9	230	35.120229	0.000025	217.857081
10	232	32.139129	0.000026	5562.861507
	Mean	32.779743	0.000085	1852.357597

Table 1 presents the result of the performance analysis of the S-G filter of polynomial order 9 to data frames of length 21 in ECG de-noising. From Table 1 it can be observed that the SNR for the ten (10) sampled ECG signals de-noised using S-G filter varies from 22.17dB to 42.80dB with a mean value of approximately 32.78dB, while the MSE varies from 0.00003 to 0.00034 with a mean value of approximately 0.0001, and the SIR varies from -299.202dB to 81559.417dB with a mean value of approximately 1852.358dB.

A comparison of the results for SNR of the present study with other researchers on ECG de-noising using other methods was carried out and the results of the present study were better. Comparison was done with the works of El-Dahshan [26] who proposed an effective hybrid scheme for the de-noising of ECG signals corrupted by non-stationary noises using the GA and DWT, Hitrangi Sawant and Harishchandra [27] who proposed the ECG signal de-noising using discrete wavelet transform, Sadhukhan and Mitra [28] who proposed an ECG noise reduction technique by suppressing the Fourier coefficient corresponding to the noise band, Sharma and Suji [29] analyzed various window techniques for de-noising each ECG signal based on FIR filters, Harjeet and Rajini [8] performed ECG signal de-noising using Savitzky-Golay filter and Discrete Wavelet Transform (DWT), Alyasseri *et al.* [30] who worked on ECG de-noising by using β-hill climbing algorithm with wavelet transform, and Ahmed *et al.* [31] who proposed the Genetic Algorithm (GA) with wavelet transform (WT) for de-noising of arrhythmia ECG signals. The results of comparison are shown in Fig. 12.

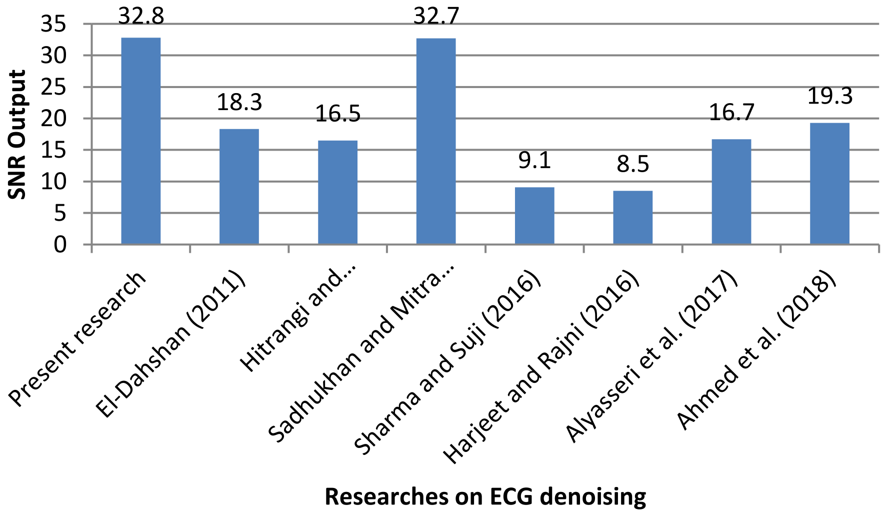

Fig. 12 Comparison of SNR output of present study with other studies

DISCUSSION

Seen from the graphical representation of the de-noised signals in time domain, the use of S-G filters preserved the height of the original signal as can easily be seen in the lightness of the graphical tracings of the de-noised signal as compared to its original signal which is darker. Also, it is evident in the graphical representation that S-G filter maintains the original shape of the signals. Likewise in the frequency domain, the graphs help to localize the noise which is obviously spread across in the case of time domain. The S-G filter proved to be a good de-noising filter and preserving the signal within the positive axes.

Findings from the performance analysis has revealed that the average SNR value is approximately 32.78dB, which implies that S-G filter is good since according to Net Spot [21] a value of 25-40dB is considered good. This finding is similar with the work of Krishnamurthy *et al.* [32] but differs greatly with the works of Sharma and Suji [29] that had an average value of 9.08dB. This is because of their methodology as they had used window-based FIR filter with a 50Hz cut-off frequency. It also differs from Harjeet and Rajini [8] that obtained an average value of 8.52dB using Discrete Wavelet Transform (DWT) even though they used S-G filter and carried out thresh-holding. Sadhukhan and Mitra [28] obtained an average value of 19.64dB which is also poor as they had used a method of suppressing the Fourier coefficient corresponding to the noise band. And finally, Sharma and Narwaria [33] obtained an average value of 4.68dB using the Gaussian window technique which is unreliable.

From the analysis of MSE, findings have revealed an average value is 0.0001 which can be approximated to zero (0). This shows how perfectly fitted our de-noised signal line is to the data point. Since according to Bruner [22] smaller values imply smaller magnitudes of error, it provides us with confidence that our assumptions about trends in the data are correct. This is similar to the findings of Harjeet and Rajini [8] that obtained 0.1201 for S-G filter and 0.0135 for DWT.

Finally, from the analysis of SIR, findings have revealed an average value of approximately 1852.358dB. According to Nnebe *et al.* [23] the higher the SIR the minimal the interference. Since the threshold value is 18dB, a SIR value of 1852.358dB implies that S-G filter does not allows co-channel interference from other radio transmitters when de-noising. This finding differs with the work of Rastogi and Mehra [15] that obtain an SIR value of 1.003dB using the Butterworth filter.

CONCLUSION

The importance of ECG signals in medical diagnosis of cardiac diseases is very important, even though noise interference can limit and degrade the quality of the signal leading to wrong diagnosis of patients, de-noising helps to maintain the quality of the signal for good diagnosis and patient therapy. The use of filters in ECG signal de-noising has proven to be one of the solutions for a good and effective ECG signal. Management of the hospitals and other cardiac health centers most understand the importance of SNR, MES and SIR values in the selection of de-noising filter. The SNR value measures the filter performance as against its internal disturbance with a threshold value of 25dB while SIR value measures its performance against external interference with a threshold value of 18dB, in both cases, the higher the value the better the performance. Unlike for MSE that measures how fitted is the de-noised signal to the useful signal; in this case, the lower the values fall towards zero (0), the better the signal. The use of S-G filter of polynomial order 9 in ECG de-noising has shown that the filter is very good in eliminating the background noise as well as maintaining a good fit for the useful signal, and also does not allow co-channel interference from other radio transmitters while de-noising. These as seen from the results of this study make the S-G filter an excellent filter for production of good quality ECG in diagnosis and treatment of cardiac patients.

DECLARATION

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Code availability: (Codes used for the simulation are presented in the Appendix)
Authors' contributions: (All authors contributed to the study conception and design, material preparation, data collection and analysis. All authors read and approved the final manuscript).

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APPENDIX

Codes

```
%%
clc;
[val, x] = plotATM('108m');%%PlotAtm is function used for reading ecg  file
%%
h=val(1,:);%% selection of ecg signal for further process
%%
Fs=360;%% sampling frequency given
t=(0:length(h)-1)/Fs;%% time for the signal
figure;
plot(t,h)%% plotting
title('Original ECG signal in time domain')
%%
u=length(h);%% calculating length of signal
K=abs(fft(h));%%converting into frequency domain
fax_bins = [0 : u-1]; %frequency axis in bins
u_2 = ceil(u/2);
figure;
plot(fax_bins(1:u_2), K(1:u_2))
xlabel('Frequency (Bins)')
ylabel('Magnitude');
title('Original ECG in frequency domain (Single-sided Magnitude spectrum
(bins))');
axis tight
ylim([0 200])
%%
%%
rd = 9;
fl = 21;

smtlb = sgolayfilt(h,rd,fl);

figure;
subplot(2,1,1)
plot(t,h)

%%

title('Original in time response')
grid

subplot(2,1,2)
plot(t,smtlb)

title('Filtered using  Savitzky-Golay in time response')
grid
%%
rd1 = 9;
fl2 = 21;

smtlb1 = sgolayfilt(K(1:u_2),rd1,fl2);%Smooth the signal by applying a
Savitzky-Golay filter of polynomial order 9 to data frames of length 21.
figure;
subplot(2,1,1)
plot(K(1:u_2))
title('Original in frequency response')
grid
```

```
subplot(2,1,2)
plot(smtlb1)

title('Filtered in Savitzky-Golay frequency response')
grid
%%

%%
for i=1:length(h)
SIR=h(i)/(h(i)-smtlb(i));
end
fprintf('Signal to interference when Savitzky-Golay is applied is %f\n',SIR);
%%
mse=0;
for i=1:length(h)
mse=mse+(smtlb(i)-h(i))^2;
end
mse=mse/length(h);
fprintf('mean squared error after Savitzky-Golay filter is applied %f\n',mse);
%%
num=0;
den=0;
for i=1:length(h)
den=den+(smtlb(i)-h(i))^2;
end
for i=1:length (h)
num=num+h(i)^2;
end
SNR = 20*log10(sqrt(num)/sqrt(den));
fprintf('signal to noise ratio after Savitzky-Golay filter is applied %f
db\n',SNR);
%%
```