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Digital Filter Design to Reduce Motion Artifacts in Electrocardiogram Signals Based on IIR Filter

Anita Miftahul Maghfiroh[1], Singgih Yudha Setiawan[1], and Muhammad Umer Farooq Mujahid[2]

[1]Department of Electromedical Engineering, Poltekkes Kemenkes Surabaya, Surabaya, 60245, Indonesia
[2]University of Health Sciences, Lahore, India

Corresponding author: Anita Miftahul Maghfiroh (e-mail: anitamiftah@poltekkesdepkes-sby.ac.id).

ABSTRACT Developed a new method to overcome motion artifacts in Electrocardiogram (ECG) signals, which often interfere with accurate clinical analysis. Motion artifacts, such as body movements, can cause significant distortions in the ECG signal, resulting in incorrect interpretation and affecting medical diagnosis. The main objective of this research is to design and implement an infinite impulse response (IIR) filter with a predetermined sequence, namely orders 2, 4, 6, and 8 to reduce motion artifacts in the ECG signal. We aim to improve ECG signal quality by preserving important ECG signal information and reducing noise caused by motion artifacts. This research contributes to developing more precise and reliable ECG signal processing techniques. The proposed method provides an effective approach to handling motion artifacts, enabling more accurate and reliable ECG interpretation by medical professionals. We used an ECG simulator that provides body movement simulation as a basis for experiments. The detected ECG signal is processed with a predetermined order IIR filter. We compare the filtered signal to the original signal to measure the effectiveness of reducing motion artifacts. Experimental results show that the applied IIR filter efficiently reduces motion artifacts in the ECG signal. The SNR assessment showed a significant improvement, proving the success of this method in maintaining ECG signal quality. The result is that in the 2nd order, the SNR value is 22.25 dB, in the 4th order the SNR value is 22.75 dB, in the 6th order the SNR value is 22.99 dB, in the 6th order the SNR value is 22.99 dB. 8 obtained an SNR value of 23dB. This study successfully demonstrated that using IIR filters in a specified order effectively reduces motion artifacts in the ECG signal, increases SNR, and maintains the integrity of clinical information in the ECG signal. The implications of this research extend to medical technology development and clinical applications, providing a strong foundation for continued research in more efficient and reliable ECG signal processing.

INDEX TERMS ECG signal, motion artifact, SNR

I. INTRODUCTION

The technique known as electrocardiography (ECG) is frequently used to gauge how well the human heart is functioning by monitoring its electrical activity. It is imperative to monitor cardiac performance as a critical indicator. The typical cardiac measurement range is 60–100 beats per minute (BPM), with BPM being the unit of measurement. Biomedical signals with non-stationary frequencies that fluctuate in response to cardiac physiological events are known as electrocardiography (ECG) signals. A vital component of heart attack prevention and monitoring is electrocardiography (ECG). Electrodes applied to the skin's surface are used to conduct leads, which record ECG signals in the frequency range of 0.05-150 Hz [1][2]. The PR interval, QRS complex, and QT interval comprise the ECG signal's features. If there is an irregularity in the patient's heart function, the physician can determine the problem from this waveform. Interference that can fatally affect the diagnosis outcomes is frequently encountered when trying to obtain a good ECG signal. Examples of this interference include breathing movements, electrical line interference at 50 Hz, and errors in the ECG processing technique. To maintain signal quality and lower the wave production error rate required for clinical acceptance, an adequate ECG filter is required [3][4].

Filters have been developed to stop interference with ECG signals in a number of earlier research. Jayant et al.'s study, for example, used an IIR filter to remove interference from power lines [5]. The study indicates that a frequency of 50 Hz can be rejected by the digital IIR filter. There is still noise even though the IIR filter being utilized is only up to second order. Faiz et al, The Cascaded multistage adaptive method is used to reject noise or artifacts [6]. The advantage of this method is that it can eliminate several artifacts from the ECG signal with low distortion and a high increase in signal-to-noise ratio. Roberta Dozio et al. created second and third-order analog high-pass filters to remove distortion from ECG recordings in order to achieve diagnostic quality [7]. Because the order used in this research was limited to order 3, it was explained that the eradication of distortion was still suboptimal. The 4th order noth filter is similarly intended to reject the 50 Hz frequency from the power line, and the 4th order LPF is also constructed with a cut-off frequency of 100 Hz [8]. Digital filter processing methods are widely used by other research to reduce signal interference or the occurrence of motion artifacts [9]–[11][12][13]. Moeyersons et al, proposed a novel method for artefact detection and quality assessment of ambulatory ECG signals using signal decomposition, feature extraction, and classification techniques with high accuracy and robustness. Limitation this research is Did not evaluate the method on different types of ambulatory ECG devices or signals [14]. Jain and Paul et al, a digital filter design has been created to reduce noise with the advantage of the method Design of filters using current amplifiers for removal of noises from ECG signal [15]. However, the weakness of this method is Did not compare the filters with other existing methods or devices. Xiang An et al. proposed an adaptive filtering method to reduce motion artifacts in wearable electrocardiogram (ECG) measurements [16]. Experimental results show that the proposed method can effectively suppress motion artifacts and achieve minimal distortion in noiseless ECG signals, compared with conventional high-pass filters. However, this study does not provide a comprehensive literature review of existing motion artifact reduction methods, and does not compare the proposed method with other state-of-the-art methods. Jianwen Ding et al., designed a new ECG electrode structure that can measure ECG signals and reference signals simultaneously [17]. A reference signal is used to reduce motion artifacts originating from accuracy and variations in the skin-electrode interface. uses an adaptive filter to separate the ECG signal from noise. The performance testing results show that the proposed electrode structure can suppress movement activity effectively and maintain signal quality stability during noncontact ECG measurement. The signal to noise ratio (SNR) of the ECG signal after noise reduction was 14 dB higher than the original ECG signal with motion artifacts. The proposed method has advantages such as simple design, easy to implement, and low cost. However, the drawback of this method is that it still requires optimization of the size of the electronic board and its weight to increase comfort of use [18][19].

Of the several research methods described previously, many researchers have made improvements to reduce motion artifacts by using various digital filter methods. However, the author has not found an analysis of the signal-to-noise ratio (SNR) results discussed from the digital filter results. Therefore, the author's aim is to compare filter orders on IIR filters, starting from orders 2, 4, 6, and 8 to get the most optimal SNR value. The contribution of this research is:

1. Optimal SNR can improve the accuracy of diagnosis, patient monitoring, and medical treatment.
2. Can help researchers and practitioners in the fields of medical science and biomedical engineering to optimize the use of this technology in practical applications.

II. MATERIALS AND METHODS

A. Experimental Setup

In this research, the ECG simulator that will be used to store various artifacts and conditions is an ECG simulator with the Fluke MPS450 brand. Furthermore, for analysis needs, researchers provide several motion treatments, including respiratory movement motion artifacts, basic artifacts, and muscle artifacts, in the simulation signal. Record the ECG signal from the simulator after certain treatments are given using leads on lead II. Record the signal in digital form which will then be analyzed off-line for filter orders. Signal Preprocessing: Cleaning signals from noise using preprocessing techniques. In this case, artifact detection and removal techniques such as motion artifacts, ground artifacts, and muscle artifacts are used. Next, the application of the IIR filter is used and compared between orders 2, 4, 6, and 8 to filter the ECG signal which is clean of artifacts. Each filter will provide different results in reducing noise and artifacts in the ECG signal. 2nd, 4th, 6th, and 8th Order Filters: These order filters Refer to the number of coefficients in the filter formula. The higher the filter level, the more complex the filter and the better its ability to reduce noise. The final stage is the analysis results: comparing the results of using IIR filters of orders 2, 4, 6, and 8 and evaluating the filter that provides the best results in reducing noise artifacts without losing important information from the ECG signal. The transfer function of the

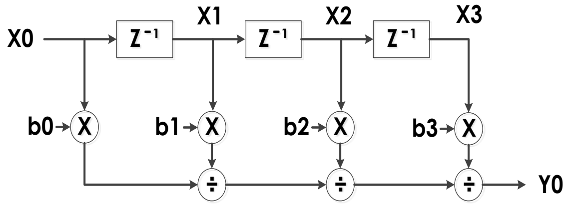


FIGURE 1. Transfer function digital filter [20]

IIR filter is explained in FIGURE 1.

The Butterworth filter is one of the most widely used conventional filter design techniques. Because of its virtually flat (maximally flat) passband amplitude response and lack of ripple, the Butterworth filter is recommended. This is an IIR filter with low frequency. Based on EQUATION 1, the IIR filter is excellent and has a large processing capacity [20].

y=b[0]*x0 + b[1]*x1 + b[2]*x2 + b[3]*x3 + b[4]*x4 - a[1]*y1 - a[2]*y2 - a[3]*y3 - a[4]*y4 (1)

where x(n) being the adaptive filter's input, y(n) being the adaptive filter's output, a(n) being the desired result, and b(n) being the adaptive algorithm's error.

1) MATERIALS AND TOOLS

In this research, the ECG Simulator is used to produce simulated ECG signals with various types of artifacts. Includes electrode cables, and connectors necessary to connect the simulator to recording equipment to obtain lead II ECG signal leads. Creating software for IIR filters with orders 2, 4, 6, and 8 for ECG signal processing. Data Storage Equipment: Hard drive or other storage media for storing recorded ECG signal data and analysis results. To measure evaluation metrics such as SNR (Signal-to-Noise Ratio), or other metrics. Visualization Software: Graphics software such as matplotlib (Python) or graphics software for creating graphs and visualization of results.

2) EXPERIMENT

In this research, the ECG simulator that will be used to store various artifacts and conditions is an ECG simulator with the Fluke MPS450 brand. Data is collected from the electrodes to obtain the heart's electrical signals which are then filtered using an analog filter circuit. The analog filter output is then digitally filtered to reduce motion artifacts. Data collection is carried out by giving certain treatments using artifact detection and removal techniques such as motion artifacts, baseline artifacts, and muscle artifacts. From this data collection, the signal-to-noise ratio (SNR) will be analyzed by comparing order digital filter methods, order IIR filters 2, 4, 6, 8. [21].

D

3) METHODS

In signal processing, the filter function is used to remove unwanted parts of the signal, such as noise, or to extract signals that will be utilized in certain conditioning, such as filter designs in a specified frequency range. There are two types of filters for designing digital filters, including recursive filters or what are called infinite impulse response filters (IIR filters) and Finite Impulse Response filters (FIR filters). Recursive filters are very useful because they bypass longer convolutions. The output of the filter is a filter impulse response which is made into a sinusoidal oscillation and decays exponentially. Because this impulse response in an infinitely long recursive filter is often referred to as infinite impulse filter response (IIR) [22]. The relationship between recursion coefficients and filter response is given by a mathematical technique called z-transform, z-transform can be used for tasks such as: converting between recursion coefficients and frequency response, combining cascade and parallel stages into one filter, designing recursive systems which emulate analog filters, etc. IIR filters are described using difference EQUATIONs , as shown in EQUATION 2 [23],

$$y(n) = b_0x(n) + b_1x(n-1) + \cdots + b_Mx(n-M) - a_1y(n-1) - \cdots - a_Ny(n-N) \quad (2)$$

where b_i, $0 \leq I \leq M$ and a_j, $1 \leq j \leq N$, represents the system coefficients and n is the time index. EQUATION 3 can also be written as follows,

$$y(n) = \sum_{i=0}^{M} b_ix(n-i) - \sum_{j=1}^{N} a_jy(n-j) \quad (3)$$

From EQUATIONs (1) and (2) it can be observed that the filter output is the weighted sum of the current input value x(n) and the previous value, namely x(n-1)….x(n-M) and the previous output value, namely y(n). -1)…. y(n-N). Assuming that all initial conditions are zero, the Z transformation described in EQUATION 4,

$$H(z) = \frac{Y(z)}{X(z)} = \frac{b_0+b_1z^{-1}+\cdots+b_Mz^{-M}}{1+a_1z^{-1}+\cdots+a_Nz^{-N}} \quad (4)$$

where H(z) is the transfer function of the system. H(z) and h(n) are called impulse responses. Next, analyze the SNR digital signal processing results to compare the filter orders described in EQUATION 5 [24],

$$SNR: \frac{\bar{S}}{\sigma_N}$$

where σ_N is the baseline and activation related to noise, and $\bar{S}$ average represents signal power. To determine the signal-to-noise ratio's (SNR) average and standard deviation, statistical analysis was performed.

B. DIAGRAM BLOCK

The instrumentation used for data collection is an electrocardiography signal detection tool. Electrodes are placed on the skin surface according to Einthoven's Equilateral Triangle to obtain lead II signals. Electrocardiogram signal detection is described in FIGURE 2.

Vol. 16, No. 4, December 2023, pp. 232-237 e-ISSN 2407-8964; p-ISSN 1907-7904

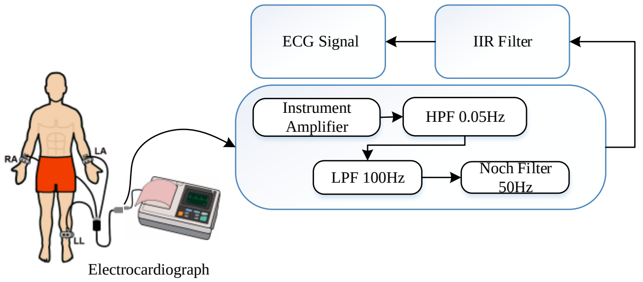


FIGURE 2. **Block diagram of the ECG signal processing system**

In FIGURE 2, it is explained that electrodes are installed on the skin surface according to what is shown by Einthoven's Equilateral Triangle to obtain lead II signals. The electrode output has a very low amplitude so an instrument amplifier with a minimum instrument amplifier gain of 100 times is required. The output from the instrument amplifier is still mixed with noise so an analog filter is needed to eliminate noise interference. The filter is designed using HPF and LPF with a filtered frequency range of 0.05 Hz - 100 Hz. The Notch Filter circuit in this research is used to eliminate 50 Hz frequency grid noise in the voltage supply and that generated by the Oscilloscope. The analog filter output is processed through a digital filter to reduce motion artifact interference in the ECG signal.

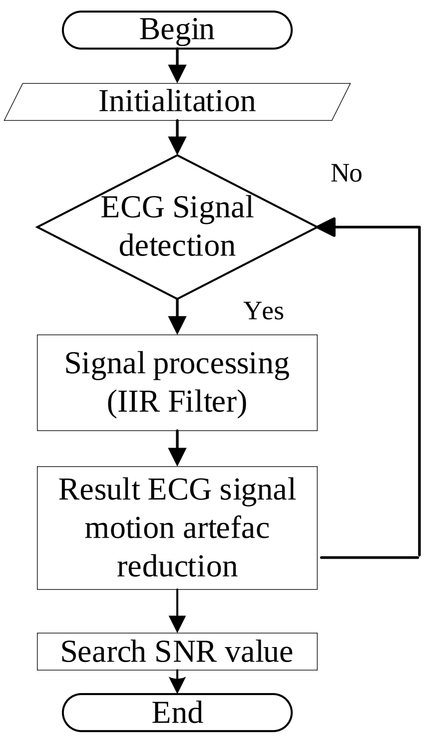


FIGURE 3. **The Flowchart of Arduino Process**

C. THE FLOWCHART

FIGURE 3 System Initialization: Prepare the system to read and detect ECG signals from the simulator or recording device. Signal Reading: Read ECG signals from a recording device or simulator to a computer system or microcontroller for digital processing. ECG Signal Detection: Use detection algorithms to identify areas where ECG signals are present in the data. This may involve the use of thresholding or QRS wave detection algorithms to detect QRS complexes in the ECG signal. Filter Process Using IIR Filter: Selection of Filter Order: Determine the IIR filter order to be used (2, 4, 6, or 8). Filter Implementation: Apply an IIR filter to the ECG signal using the appropriate IIR filter formula. This process involves passing the signal through a filter using previously calculated filter coefficients. In this research, the IIR filter design used uses a bandwidth frequency of 0.05Hz to 40 Hz. Signal Filtering: Filter the ECG signal using the selected IIR filter. The IIR filter is used to reduce artifacts, including motion artifacts, from the ECG signal. Process Artifact Reduction: IIR filters can be specifically designed to reduce motion artifacts. In this context, IIR filters are used to reduce interference caused by body movements or physical activity that may appear in the ECG signal. Next, calculate the Signal-to-Noise Ratio (SNR): After the filtering process is complete, calculate the SNR value of the filtered ECG signal and the unfiltered ECG signal (original signal). SNR is the ratio between the strength of the ECG signal and the strength of the noise in the signal. Compare the SNR value of the filtered signal with the original signal. A higher SNR indicates that the true ECG signal has been well preserved while noise and artifacts have been successfully reduced. SNR Analysis: Evaluate the SNR results to assess the extent to which the IIR filter has been successful in reducing noise and artifacts. Interpret the results of the SNR analysis and determine how well the IIR filter has succeeded in cleaning the ECG signal from artifacts, including motion artifacts.

III. RESULT

The electrodes installed in the ECG Simulator with the ECG simulator that will be used to store various artifacts and conditions is an ECG simulator with the Fluke MPS450 brand. Furthermore, for analysis needs, researchers provide several motion treatments, including respiratory movement motion artifacts, basic artifacts, and muscle artifacts, in the simulated signal.

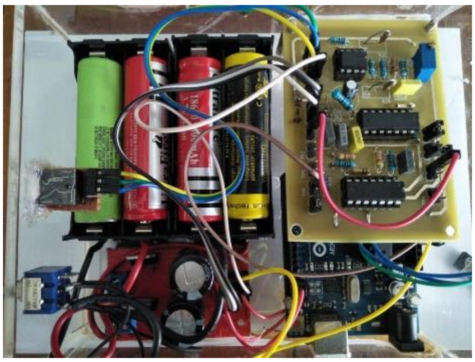


FIGURE 4. **Desain ECG Instrumentation**

Vol. 16, No. 4, December 2023, pp. 232-237 e-ISSN 2407-8964; p-ISSN 1907-7904

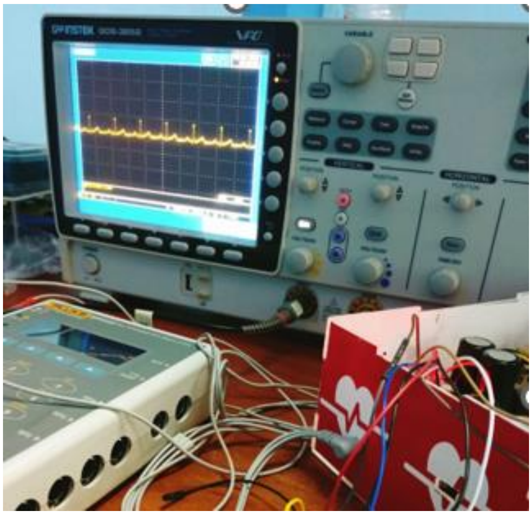
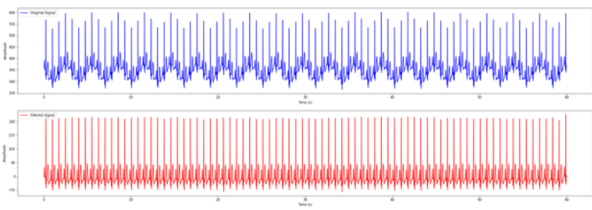


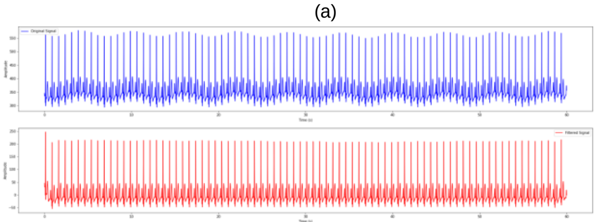
FIGURE 5. **The results of the ECG signal display on the oscilloscope**

A. DESIGN MODULE BUILD

This research was carried out to obtain the best digital filter results for reducing motion artifacts using an IIR filter. As an analysis of the results of the filter, the SNR value was sought to carry out the appropriate filter analysis process. FIGURE 4



(a)



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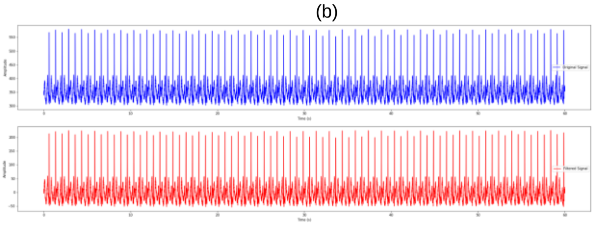
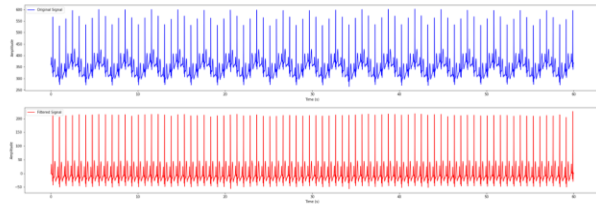


(c)

FIGURE 6. a) **respiratory movement motion artifacts,** b) **basic artifacts, and,** c) **muscle artifacts, in the simulated signal**

shows the ECG instrumentation used to collect data on the ECG simulator and analyzed off-line for the ECG signal processing stage. Testing the entire ECG instrument circuit uses a Fluke MPS450 ECG phantom connected to the instrument circuit, then the output signal display is displayed on the oscilloscope. The data collection technique is explained in FIGURE 5.



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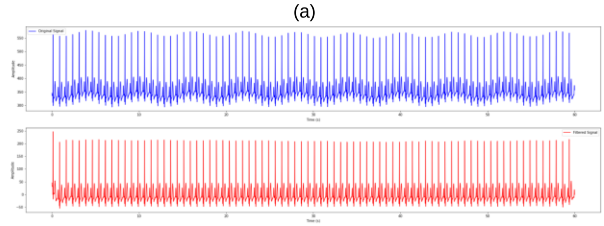

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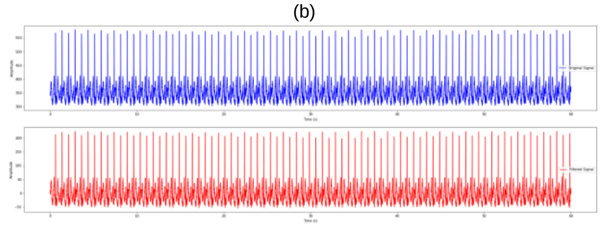


(c)

FIGURE 7. a) **respiratory movement motion artifacts** b) **basic artifacts, and** c) **muscle artifacts, in the simulated signal**

B. FILTER PERFORMANCE TEST RESULTS

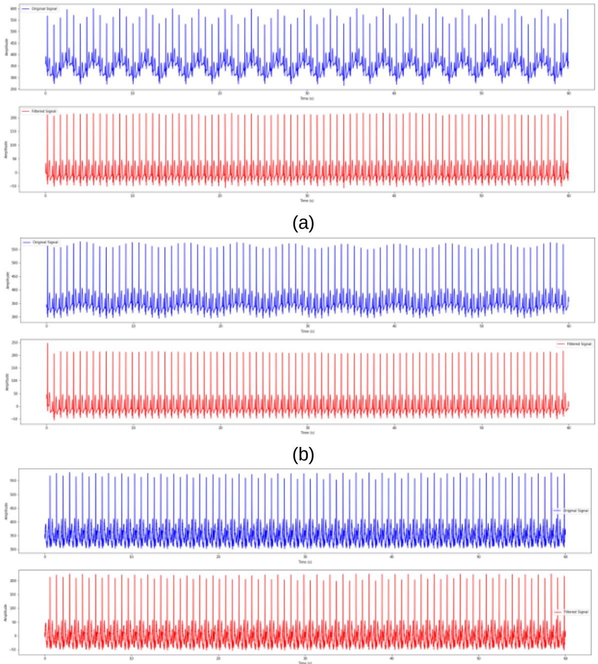
After obtaining the ECG signal, Furthermore for analysis needs, researchers provide several motion treatments, including respiratory movement motion artifacts, basic artifacts, and muscle artifacts, in the simulated signal using an ECG simulator. In FIGURES 6, 7, 8, 9, the results of signal processing using IIR filters with order 2, 4, 6 and 8 are explained. FIGURES 6 is the result of a 2nd order IIR filter using three signal simulations using the ECG simulator.

FIGURES 7 is the result of a 4th order IIR filter using three signal simulations using the ECG simulator. including respiratory movement motion artifacts, basic artifacts, and muscle artifacts, in the simulated signal. FIGURES 8 is the result of a 6th order IIR filter using three signal simulations using the ECG simulator. FIGURES 8 is the result of a 8th order IIR filter using three signal simulations using the ECG simulator. including respiratory movement motion artifacts, basic artifacts, and muscle artifacts, in the simulated signal. FIGURE 8 depicts the results of an 8th order IIR filter applied to three signal simulations using the ECG simulator. These simulations likely include respiratory motion artifacts, ground artifacts, and muscle artifacts in the simulated signal. Based on this information, FIGURE 8 shows the effectiveness of an 8th order IIR filter in reducing or eliminating these artifacts from the simulated ECG signal.

Vol. 16, No. 4, December 2023, pp. 232-237 e-ISSN 2407-8964; p-ISSN 1907-7904

B. SNR MEASUREMENT

To determine the reliability of the digital filter system, data was collected by signal processing using different filter sequences, namely orders 2, 4, 6 and 8 using frequency bandwidths of 0.05Hz to 40Hz as shown in TABLE 1. Evaluate the SNR results to assess the extent of the filter's success. IIR in reducing noise and artifacts (SNR) is determined in the manner described in PSEUDECODE 1.



(a)

(b)

(c)

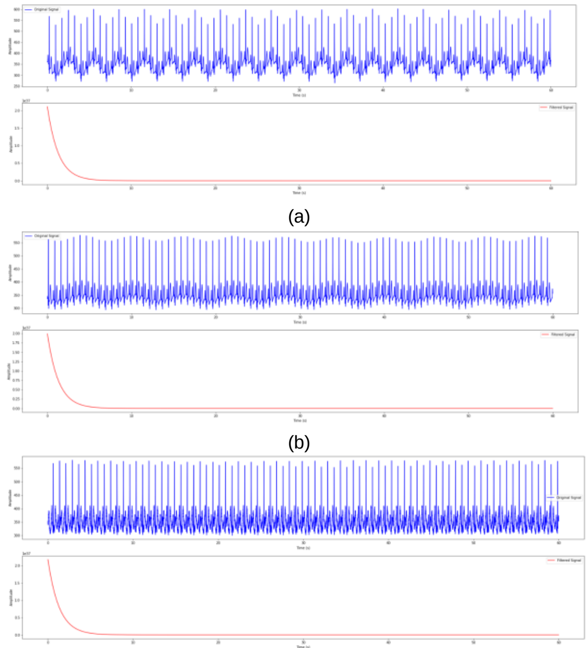
FIGURE 8. a) respiratory movement motion artifacts b).basic artifacts, and c). muscle artifacts, in the simulated signal

TABLE 1

Evaluation of SNR results to assess the extent to which the IIR filter

SNR Value			
IIR Filter (2^{nd})	IIR Filter (4^{th})	IIR Filter (6^{th})	IIR Filter (8^{th})
22,25 dB	22,75 dB	22,99 dB	23,00 dB

In TABLE 1, it is explained that in the 2nd order an SNR value is obtained of 22,25 dB, in the 4th order an SNR value is obtained of 22,75 dB, in the 6th order an SNR value is obtained of 22,99 dB, in the 8th order an SNR value is obtained of 23 dB.



(a)

(b)

(c)

FIGURE 9. a) respiratory movement motion artifacts b) basic artifacts, and, c) muscle artifacts, in the simulated signal

PSEUDECODE 1. Calculation of SNR values

1.	**% SNR Calculation for Orde 2**
	signal_power2 = sum(y_orde2.^2);
	noise_power2 = sum((x - y_orde2).^2);
	SNR2 = 10 * log10(noise_power2/ signal_power2);

2.	**% SNR Calculation for Orde 4**
	signal_power4 = sum(y_orde4.^2);
	noise_power4 = sum((x - y_orde4).^2);
	SNR4 = 10 * log10(noise_power4/ signal_power4);

3.	**% SNR Calculation for Orde 6**
	signal_power6 = sum(y_orde6.^2);
	noise_power6 = sum((x - y_orde6).^2);
	SNR6 = 10 * log10(noise_power6/ signal_power6);

4.	**% SNR Calculation for Orde 8**
	signal_power8 = sum(y_orde8.^2);
	noise_power8 = sum((x - y_orde8).^2);
	SNR8 = 10 * log10(noise_power8/ signal_power8);

IV. DISCUSSION

The findings from this experiment show that the use of IIR filters with different orders produces very different results in reducing motion artifacts in the ECG signal. In the cases of orders 2, 4, and 6, although there are nominal differences in SNR values, the signal results obtained do not show significant differences in terms of clarity. However, order 8 shows unreadable results, despite having a relatively high SNR value of around 23 dB. The minimal difference between SNR values at orders 2, 4, and 6 raises the question of the added value provided by increasing the filter order. In this context, results close to 22 dB indicate that the true ECG signal dominates noise and motion artifacts at that level. Therefore, increasing the filter order from 6 to 8 does not provide a significant improvement in signal quality. Conversely, order 8 may have introduced additional distortion or significant loss of information in the signal, explaining why the filtered signal at order 8 is unreadable. The implication of these findings is that in the context of reducing motion artifacts in ECG signals, higher filter orders do not always produce better results.

In other research Xiaowen Xu et al [25], discusses movement artifact reduction methods based on empirical wavelet transform (EWT) and wavelet thresholding (WT) for non-contact ECG monitoring systems. The advantage of this method is that it can adapt to the characteristics of the ECG signal and motion artifacts without requiring the selection of appropriate wavelet functions and thresholds. This method can also maintain the original ECG waveform well and reduce signal distortion. The weakness of this method is that it requires a more complex computational process and takes longer than the discrete wavelet transform (DWT) or empirical mode decomposition (EMD) methods. This method can also be affected by the choice of transition width parameters and the number of spectral segments. The decision in selecting filter order must be carefully considered to ensure that the integrity of the ECG signal is maintained. Further research could be conducted to explore other factors such as artifact type, frequency variations, and sustainability of the filtering process against other signal quality metrics. These results can help in the development of signal processing techniques that are more accurate and efficient in dealing with motion artifacts in ECG signals, supporting the improvement of more precise and reliable medical diagnoses.

V. CONCLUSION

The main objective of this research is to design and implement an IIR filter with a predetermined order to reduce motion artifacts in the ECG signal. This study successfully demonstrated that the use of an IIR filter with a defined order effectively reduces motion artifacts in the ECG signal, increases SNR, and maintains the integrity of clinical information in the ECG signal. The minimal difference between SNR values at orders 2, 4, and 6 raises the question of the added value provided by increasing the filter order. In this context, results close to 22 dB indicate that the true ECG signal dominates noise and motion artifacts at that level. Therefore, increasing the filter order from 6 to 8 does not provide a significant improvement in signal quality. Conversely, order 8 may have introduced additional distortion or significant loss of information in the signal, explaining why the filtered signal at order 8 is unreadable. In future research, develop better filtration techniques or explore other aspects of ECG signal processing.

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