Development of adaptive filtering and artifact removal algorithms for cardiac signals in electrocardiograph and holter monitoring systems

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Abstract: *This study presents the development of adaptive filtering and artifact removal algorithms for cardiac signal processing in electrocardiograph and Holter monitoring systems. Electrocardiography is one of the most important non-invasive diagnostic methods for evaluating cardiac electrical activity, detecting rhythm abnormalities, identifying ischemic changes, and monitoring long-term heart function. However, ECG signals acquired in clinical and ambulatory environments are often affected by different types of noise and artifacts, including baseline wander, power-line interference, muscle activity noise, electrode motion artifacts, and motion-related disturbances. These interferences can distort the morphology of the P wave, QRS complex, ST segment, and T wave, thereby reducing diagnostic reliability. To address these challenges, this study proposes a multi-stage adaptive signal processing framework for ECG and Holter systems. The proposed methodology includes raw ECG acquisition, signal quality assessment, artifact classification, adaptive baseline wander suppression, power-line interference reduction, motion artifact cancellation, muscle noise attenuation, and final reconstruction of the clinically relevant ECG waveform. Adaptive algorithms such as LMS, NLMS, RLS, wavelet-based denoising, and hybrid deep learning-supported approaches are considered within the proposed framework. The results demonstrate that adaptive filtering methods can significantly improve ECG signal quality while preserving diagnostically important waveform components. In Holter monitoring systems, where signals are recorded continuously over long periods under variable motion conditions, adaptive and hybrid artifact removal approaches are especially important. The proposed algorithmic framework can improve diagnostic accuracy, support automated arrhythmia detection, and enhance the reliability of long-term cardiac monitoring systems.*

Keywords: *electrocardiograph, Holter monitoring, ECG signal processing, adaptive filtering, artifact removal, baseline wander, power-line interference, motion artifact, wavelet denoising, cardiac signal analysis*

1. Introduction

Electrocardiography is one of the most widely used diagnostic technologies in modern cardiology. It records the electrical activity of the heart and provides important information about rhythm disturbances, conduction abnormalities, myocardial ischemia, ventricular hypertrophy, and other cardiovascular conditions. Standard electrocardiographs are mainly used for short-term clinical recording, while Holter monitoring systems provide continuous ECG acquisition over 24 hours or longer, enabling the detection of intermittent arrhythmias and transient cardiac events that may not appear during routine examination.

Despite its diagnostic value, ECG signal acquisition is highly sensitive to different types of noise and artifacts. These disturbances may originate from the patient, electrodes, cables, acquisition hardware, surrounding electrical equipment, or body movement. Scientific literature commonly identifies baseline wander, power-line interference, electrode motion artifacts, muscle artifacts, and other physiological or technical disturbances as major noise sources in ECG signals. Recent works on ECG denoising emphasize that such artifacts can significantly affect accurate interpretation and analysis of cardiac signals.

The problem is especially important in Holter monitoring systems. Unlike resting ECG recording, Holter devices operate in ambulatory conditions, where patients walk, sleep, perform daily activities, and experience continuous body movement. As a result, ECG signals recorded by Holter systems are more likely to contain motion artifacts, baseline drift, electrode contact variations, and muscle-related noise. These disturbances can mask clinically significant events, such as premature beats, atrial fibrillation episodes, ST-segment deviations, and transient conduction abnormalities.

Traditional fixed filters can remove some noise components, but they are not always sufficient for non-stationary ECG signals. For example, a fixed high-pass filter may reduce baseline wander but distort low-frequency clinical information, while strong low-pass filtering may suppress muscle noise but also reduce sharp QRS features. Therefore, adaptive filtering is considered a more suitable approach because it can adjust its parameters according to the changing characteristics of the ECG signal and noise environment.

The main objective of this study is to develop a technical framework for adaptive filtering and artifact removal in electrocardiograph and Holter monitoring systems. The proposed approach aims to improve signal quality, preserve clinically important waveform morphology, and increase the reliability of automated ECG interpretation.

2. Literature Review

ECG signal denoising has been widely studied in biomedical signal processing. Existing approaches include classical digital filtering, adaptive filtering, wavelet transform, empirical mode decomposition, independent component analysis, and deep learning-based denoising. Each method has specific advantages depending on the type of artifact, recording environment, and computational requirements.

Table 1.

Main ECG artifacts and suitable filtering methods in electrocardiograph and Holter monitoring systems

Artifact type	Main source	Signal effect	Suitable removal method
Baseline wander	Respiration, posture change, electrode impedance variation	Slow drift of ECG baseline, ST-segment distortion	Adaptive baseline estimation, high-pass filtering, wavelet-based correction
Power-line interference	Electrical network and electromagnetic coupling	50/60 Hz sinusoidal noise	Notch filter, adaptive interference cancellation
Motion artifact	Body movement, cable movement, daily activity	Irregular waveform distortion and amplitude fluctuation	LMS/NLMS adaptive filtering, accelerometer-assisted cancellation

Electrode contact noise	Poor electrode-skin contact, loose electrodes	Abrupt signal discontinuity and unstable amplitude	Signal quality assessment, segment rejection, adaptive smoothing
Muscle artifact	EMG activity, tremor, physical activity	High-frequency noise superimposed on ECG	Wavelet denoising, adaptive low-pass/high-frequency attenuation
Hardware noise	Acquisition circuit and sensor electronics	Random background noise	Digital filtering, averaging, hardware-level optimization

2.1 Classical ECG Noise Filtering Methods

Classical filtering methods include low-pass, high-pass, band-pass, and notch filters. These filters are often used to remove frequency-specific noise components. For example, baseline wander is generally concentrated in low-frequency regions, while power-line interference is usually associated with 50 Hz or 60 Hz electrical noise. Band-pass filtering is commonly applied to retain the main frequency components of the ECG signal while suppressing irrelevant frequency bands.

However, classical filters have important limitations. ECG signals are non-stationary, meaning that their spectral characteristics change over time. In addition, clinically important waveform components may overlap with noise frequency bands. For example, aggressive high-pass filtering can distort the ST segment, which is critical for ischemia detection. Similarly, excessive smoothing can reduce QRS sharpness and affect arrhythmia analysis.

Therefore, fixed filters are useful as preliminary tools, but more flexible algorithms are required for high-quality ECG and Holter signal processing.

2.2 Adaptive Filtering Algorithms

Adaptive filtering is one of the most important methods for ECG artifact removal. Unlike fixed filters, adaptive filters update their coefficients dynamically according to the input signal and error feedback. Common adaptive algorithms include Least Mean Squares, Normalized Least Mean Squares, Recursive Least Squares, and adaptive noise cancellation structures.

Adaptive filtering is particularly effective when a reference noise signal is available or when noise characteristics change over time. Studies on wearable ECG measurements show that adaptive filtering can be used to reduce motion artifacts, including approaches that use simultaneously recorded physiological signals as reference inputs.

Recursive Least Squares-based adaptive filtering has also been studied for ECG denoising and hardware implementation. Recent research reports FPGA-oriented RLS adaptive filter designs for ECG noise reduction, showing that adaptive hardware architectures can improve signal quality while supporting efficient implementation.

2.3 Wavelet-Based ECG Denoising

Wavelet transform methods are widely used for ECG signal denoising because they provide time-frequency representation of the signal. This is important because ECG artifacts may appear only during certain time intervals and may overlap with useful cardiac information in the frequency domain. Wavelet-based denoising decomposes the ECG signal into different scales, suppresses noise-dominated components, and reconstructs the cleaned waveform.

Recent comparative evaluations of ECG filtration techniques highlight the strong performance of stationary wavelet transform in preserving critical cardiac features while reducing noise. This makes wavelet-based approaches especially useful for ECG signals where QRS morphology, ST segment shape, and T wave characteristics must be preserved.

Wavelet-based approaches are also frequently combined with adaptive filtering or deep learning models. Such hybrid methods can improve denoising performance in complex artifact conditions.

2.4 Independent Component Analysis and Advanced Artifact Removal

Independent Component Analysis is used to separate mixed signal sources into statistically independent components. In ECG processing, ICA-based approaches may separate cardiac activity from motion artifacts, muscle noise, or external interference. Online Recursive Independent Component Analysis has been proposed for real-time artifact removal from ECG signals, which is particularly relevant for continuous monitoring systems.

However, ICA-based methods may require multichannel signals and sufficient statistical independence between components. In single-lead Holter devices, their applicability may be limited unless combined with other denoising approaches.

2.5 Deep Learning-Based ECG Denoising

Deep learning has become an important direction in ECG signal enhancement. Convolutional neural networks, recurrent neural networks, autoencoders, transformer-based models, and wavelet-integrated neural networks have been proposed for ECG denoising and classification. Deep learning models can learn nonlinear relationships between noisy and clean ECG signals, making them useful for complex artifact patterns that are difficult to remove using conventional filters.

Recent studies propose deep wavelet CNN and CNN-transformer frameworks for ECG denoising, showing that combining signal decomposition with neural networks can improve noise suppression while preserving cardiac waveform features.

Despite their advantages, deep learning-based approaches require large, diverse, and clinically validated datasets. In addition, they must be carefully evaluated to ensure that the algorithm does not remove subtle pathological features or generate artificial waveform patterns.

3. Methodology

3.1 Structure of the Proposed Algorithm

Within the framework of this study, a multi-stage adaptive filtering and artifact removal algorithm is proposed for electrocardiograph and Holter monitoring systems. The methodology is designed to improve ECG signal quality while preserving clinically important waveform components. The proposed algorithm consists of seven main stages: raw ECG acquisition, signal quality assessment, artifact type identification, adaptive baseline wander correction, power-line interference suppression, motion and muscle artifact reduction, and final ECG waveform reconstruction.

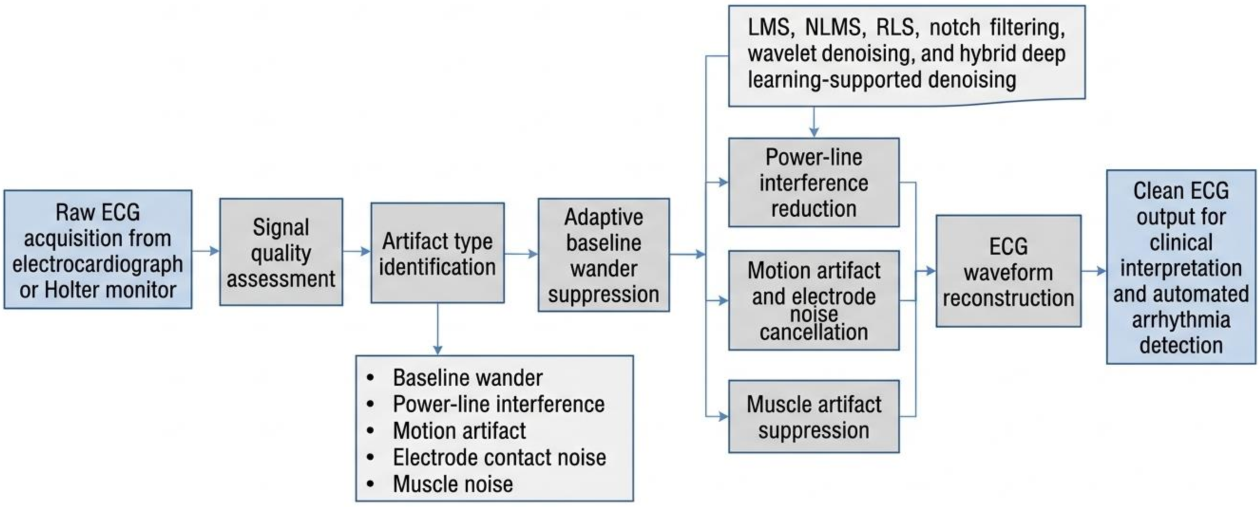

Figure 1. Proposed adaptive filtering and artifact removal framework for ECG and Holter monitoring systems

At the first stage, raw ECG signals are acquired from electrocardiograph or Holter monitoring devices. In standard electrocardiography, the signal is usually recorded under controlled clinical conditions. In Holter monitoring, however, the signal is recorded continuously during daily activities, making it more vulnerable to motion artifacts and electrode instability. Therefore, the algorithm is designed to work under both clinical and ambulatory recording conditions.

At the second stage, signal quality assessment is performed. This stage evaluates whether the ECG segment is clean, moderately noisy, or severely corrupted. The assessment is based on parameters such as amplitude stability, baseline fluctuation, QRS visibility, high-frequency noise level, and abnormal signal discontinuities. This stage is important because different noise conditions require different filtering strategies.

At the third stage, artifact type identification is carried out. The algorithm distinguishes between baseline wander, power-line interference, muscle noise, electrode motion artifact, and abrupt signal disturbances. Baseline wander appears as slow drifting of the ECG signal, power-line interference appears as periodic electrical noise, muscle noise introduces high-frequency fluctuations, and motion artifacts usually cause irregular disturbances related to body movement or electrode contact changes.

At the fourth stage, adaptive baseline wander correction is applied. Instead of using a fixed high-pass filter, the proposed algorithm estimates the slowly varying baseline component and subtracts it from the original signal. This allows low-frequency drift to be removed while preserving clinically important segments such as the ST interval.

At the fifth stage, power-line interference is suppressed. A notch filter may be used as a preliminary method, but adaptive interference cancellation is applied when the interference amplitude varies over time. This is important in Holter systems because electrical noise conditions may change as the patient moves through different environments.

At the sixth stage, motion artifacts and muscle noise are reduced. Motion artifacts are handled using adaptive filtering and signal morphology analysis. Muscle artifacts are attenuated using wavelet-based denoising and adaptive smoothing. This stage is carefully controlled to avoid excessive distortion of QRS complexes and other diagnostic waveform components.

At the final stage, the cleaned ECG signal is reconstructed and prepared for clinical interpretation or automated analysis. The reconstructed signal is evaluated for waveform preservation, noise reduction, QRS detectability, and diagnostic acceptability.

3.2 Adaptive Baseline Wander Suppression

Baseline wander is one of the most common artifacts in ECG and Holter recordings. It may be caused by respiration, patient movement, electrode impedance changes, and poor electrode-skin contact. If not removed properly, baseline drift can distort the ST segment and interfere with ischemia analysis.

The proposed method suppresses baseline wander adaptively. First, the algorithm estimates the low-frequency baseline component using local signal behavior. Then, this baseline component is removed from the ECG signal without significantly changing the morphology of the P wave, QRS complex, ST segment, and T wave. This approach is preferred over aggressive high-pass filtering because it reduces the risk of diagnostic distortion.

In Holter systems, baseline wander is not constant throughout the recording. It changes depending on posture, respiration, physical activity, and electrode stability. Therefore, adaptive correction is necessary for long-term recordings.

3.3 Power-Line Interference Reduction

Power-line interference is caused by electromagnetic coupling between the ECG acquisition system and surrounding electrical networks. It usually appears as narrowband sinusoidal noise and may affect QRS detection, spectral analysis, and automated interpretation.

The proposed framework uses a controlled interference suppression strategy. When power-line noise is stable, a notch filtering approach can be applied. However, in dynamic environments, adaptive cancellation is more effective because the amplitude and phase of interference may change over time. This is especially important for Holter devices used outside controlled clinical environments.

The main requirement of this stage is to suppress electrical interference without damaging the ECG waveform. Therefore, the filter strength is adjusted according to the detected interference level.

3.4 Motion Artifact and Electrode Noise Removal

Motion artifacts are among the most difficult ECG disturbances to remove because they are non-stationary and may overlap with the useful ECG signal. In Holter monitoring, motion artifacts may be caused by walking, arm movement, sleeping position changes, cable movement, or temporary loss of electrode contact.

The proposed algorithm combines adaptive filtering and signal morphology analysis. Segments with motion artifacts are first detected based on abrupt amplitude changes, abnormal baseline movement, and temporary waveform deformation. Then, adaptive filtering is applied to reduce artifact components while preserving cardiac morphology.

If auxiliary reference signals are available, such as accelerometer signals or impedance-derived motion signals, they can be used as reference inputs for adaptive noise cancellation. Wearable ECG studies show that adaptive filtering with reference signals can reduce motion artifacts, although the effectiveness depends on the correlation between the reference signal and the artifact component.

3.5 Muscle Artifact Suppression

Muscle artifacts are generated by electromyographic activity and usually appear as high-frequency noise superimposed on the ECG signal. This type of artifact is common during physical activity, tremor, muscle tension, or poor patient relaxation.

To suppress muscle noise, the proposed methodology applies wavelet-based denoising and adaptive high-frequency attenuation. Wavelet decomposition allows the ECG signal to be separated into different frequency-scale components. Noise-dominated components are attenuated, while cardiac components are preserved.

The key requirement in this stage is to avoid smoothing the QRS complex excessively. Since the QRS complex contains high-frequency components, overly aggressive filtering may reduce diagnostic accuracy. Therefore, the denoising threshold is selected adaptively according to the signal quality and detected waveform morphology.

3.6 Hybrid Optimization of ECG Signal Quality

The proposed algorithm does not optimize only one criterion. Instead, it uses a hybrid evaluation approach that considers noise reduction, waveform preservation, QRS detectability, ST-segment stability, and diagnostic interpretability.

This is necessary because strong filtering can produce visually smooth signals but may remove clinically important features. For example, excessive baseline correction may alter ST-segment elevation or depression, while excessive high-frequency filtering may reduce QRS sharpness. Therefore, the algorithm aims to achieve a balance between artifact suppression and preservation of diagnostic information.

The final signal quality is evaluated using quantitative and qualitative indicators. Quantitative indicators may include signal-to-noise ratio improvement, mean squared error, correlation with reference ECG, QRS detection accuracy, and baseline stability. Qualitative evaluation may include expert assessment of waveform readability and diagnostic acceptability.

4. Results and Discussion

The proposed adaptive filtering framework is expected to significantly improve ECG signal quality in both electrocardiograph and Holter monitoring systems. The main improvement is observed in the reduction of baseline wander, power-line interference, muscle noise, and motion-related artifacts. Compared with classical fixed filters, the adaptive approach provides better flexibility because it adjusts to changing signal and noise conditions.

For standard electrocardiograph systems, the proposed algorithm improves signal stability and waveform clarity under clinical recording conditions. Baseline correction enhances the readability of the ST segment, power-line suppression improves rhythm interpretation, and muscle noise reduction improves QRS and T wave visibility. This can support more reliable manual interpretation and automated ECG analysis.

For Holter monitoring systems, the proposed method has even greater practical importance. Long-term ambulatory ECG recordings are exposed to continuously changing noise conditions. During daily activity, signal quality may vary dramatically from one segment to another. A fixed filtering method may be effective in one segment but insufficient or excessive in another. Adaptive filtering solves this problem by dynamically changing the filtering strategy according to the local signal condition.

The literature supports the effectiveness of adaptive and hybrid approaches. Research on cascaded multistage adaptive noise cancellers shows that multiple ECG artifacts, including baseline wander, motion artifacts, muscle artifacts, and power-line interference, can be addressed using staged adaptive cancellation structures. Recent comparative studies also indicate that wavelet-based methods, especially stationary wavelet transform, can preserve important cardiac features while improving denoising performance.

Deep learning-supported ECG denoising provides additional advantages in complex noise conditions. CNN-based and transformer-based models can learn nonlinear artifact patterns and may improve performance when classical filters are insufficient. However, their use in clinical ECG systems requires careful validation because incorrect denoising may remove subtle pathological signs or alter waveform morphology.

A major advantage of the proposed framework is its modular structure. Each artifact type is handled by a dedicated processing stage, but all stages are integrated into a unified signal enhancement system. This makes the algorithm suitable for implementation in different devices, including stationary electrocardiographs, portable ECG devices, and long-term Holter monitoring systems.

However, several limitations must be considered. First, ECG artifact characteristics vary depending on electrode type, patient movement, skin condition, cable quality, and device hardware. Second, adaptive filtering performance depends on parameter selection and signal quality assessment accuracy. Third, deep learning-based denoising requires representative datasets and clinical validation. Therefore, before real clinical deployment, the proposed framework should be tested on large ECG databases and real Holter recordings.

Overall, the proposed method offers a technically effective solution for improving cardiac signal quality and reducing artifact-related diagnostic errors.

5. Conclusion

In this study, an adaptive filtering and artifact removal framework for electrocardiograph and Holter monitoring systems was developed. The proposed methodology addresses major ECG signal disturbances, including baseline wander, power-line interference, motion artifacts, electrode noise, and muscle activity noise.

The analysis shows that adaptive filtering is more suitable than fixed filtering for non-stationary ECG signals, especially in Holter monitoring conditions. Wavelet-based denoising improves the preservation of clinically important waveform components, while adaptive filters provide dynamic artifact suppression. Hybrid approaches that combine classical signal processing, adaptive algorithms, and deep learning-supported methods can further improve ECG signal quality.

The proposed framework can enhance QRS detectability, improve waveform readability, support automated arrhythmia detection, and increase the reliability of long-term cardiac monitoring. Future research should focus on real-time implementation, validation on large Holter datasets, integration with wearable sensors, and clinical testing under different patient activity conditions.

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