The Method and Algorithm for Detecting the Fetal ECG Signal in the Presence of Interference

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Abstract

This article discusses the importance of timely and accurate detection of fetal distress during pregnancy to reduce the risk of adverse outcomes. One non-invasive method of fetal monitoring is through the use of fetal cardiodiagnostic systems, which record the fetal ECG signal. However, selecting a reliable fetal ECG signal can be challenging, as the signal may be weak and prone to interference. The article presents several existing methods for extracting useful fetal ECG signals from a mixture, including blind signal separation, adaptive filtering, synphase method, component method, spectral method, and bispectral processing. However, the limitations of these methods make it necessary to develop a new method that can consider time-frequency characteristics and phase-time parameters of the ECG signal simultaneously. The article proposes a new algorithm and method for extracting fetal ECG signals, which involves several steps, including registration of maternal ECG signals, synphase detection of fetal ECG signals and adaptive filtering. The proposed method was tested on a generated ECG signal and was found to be effective in extracting the fetal ECG signal from noisy and artifact-containing signals. The method and algorithm for detecting the fetal ECG signal in the presence of obstacles is implemented in the MATLAB environment.

Keywords

Fetal cardiodiagnostic systems, fetal ECG signal, maternal ECG signals, method and algorithm for detecting, synphase method, adaptive filter, low-pass filter, high-pass filter, MATLAB.

1. Introduction

Congenital heart defects, a type of birth defect that can impact the structure and function of the heart, have claimed an estimated 1.5 million lives globally in 2020, according to the World Health Organization (WHO) latest data in 2021. Shockingly, the majority of these deaths occurred in infants within their first month of life, underlining the urgent need for improved diagnosis and treatment of heart defects in newborns.

The WHO's data highlights the significant burden of congenital heart defects on global health, and the importance of addressing this issue. Failure to diagnose and treat these defects can lead to serious health complications and even death, making it critical to prioritize efforts towards better understanding, diagnosis, and treatment of this condition [1].

Timely and accurate detection of fetal distress during pregnancy is crucial in order to reduce the risk of adverse outcomes. To ensure the health of both the mother and future child, diagnostic methods for studying the cardiovascular system of the fetus aim to be non-invasive. One method of fetal monitoring is through the use of fetal cardiodiagnostic systems, which record the fetal ECG signal, which is a combination of useful fetal and maternal ECG signals. However, selecting a reliable fetal ECG signal can be challenging, as the signal may be weak and prone to interference [2, 3, 7, 10, 17, 18].

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The following electrocardiographic systems have become widely used for fetal ECG registration: CardioLab+, CardioCE+ (NTC "KHAI-MEDIKA", Ukraine), fetal monitors BIONET (UMAmed, Ukraine-Korea), ECG monitors "FEMO" (MEDCO Electronics Systems, Israel), "CARE 2000", (University of Nottingham, Netherlands), fetal monitors of the Sonicaid series modifications Team, (Oxford Medical Solutions, ZOLL Medical Corporation, Ukraine-USA), DiaCard (AOZT "Solveig", Kyiv), electrocardiographs CARDIOLAB BABY-Card (Ukraine, Kharkiv), GY-EXPL (China), KAGUWI KGW-6000 (China), BeatleIC (Belgium).

The following methods of analysis are the most effective for extracting useful fetal ECG signals from a mixture:

1. Blind signal separation (E.C. Karvounis, M.G. Tsipouras, C. Papaloukas, D. G. Tsalikakis, K. K. Naka, D. I. Fotiadis);
2. Adaptive filtering (Singer Y.L., Zarzoso V., Millet-Roig J., Nandi A.K.);
3. Synphase (Kmet O.A.) and component (Andrus S.I.) methods;
4. Spectral method (Dorosh N.V., Kuchmiy G.L., Borys Yu.A., Polulikh R.I.);
5. Bispectral processing (Vyunytskyi O., Shulgin V., Totskyi O., Sharonov V.);
6. The method based on the Neyman-Pearson criterion (Khvostivskyy M., Yavorska Ye.) [10].

The limitations of the existing methods arise from their inability to consider time-frequency characteristics and the phase-time parameters of the ECG signal simultaneously, which are crucial for accurate analysis of fetal ECG signals. This makes it necessary to develop a new method that can address these issues and provide more reliable results.

2. Algorithm for extracting fetal ECG signal

The proposed algorithm for fetal ECG extraction, which is shown in Figure 1, involves several steps.

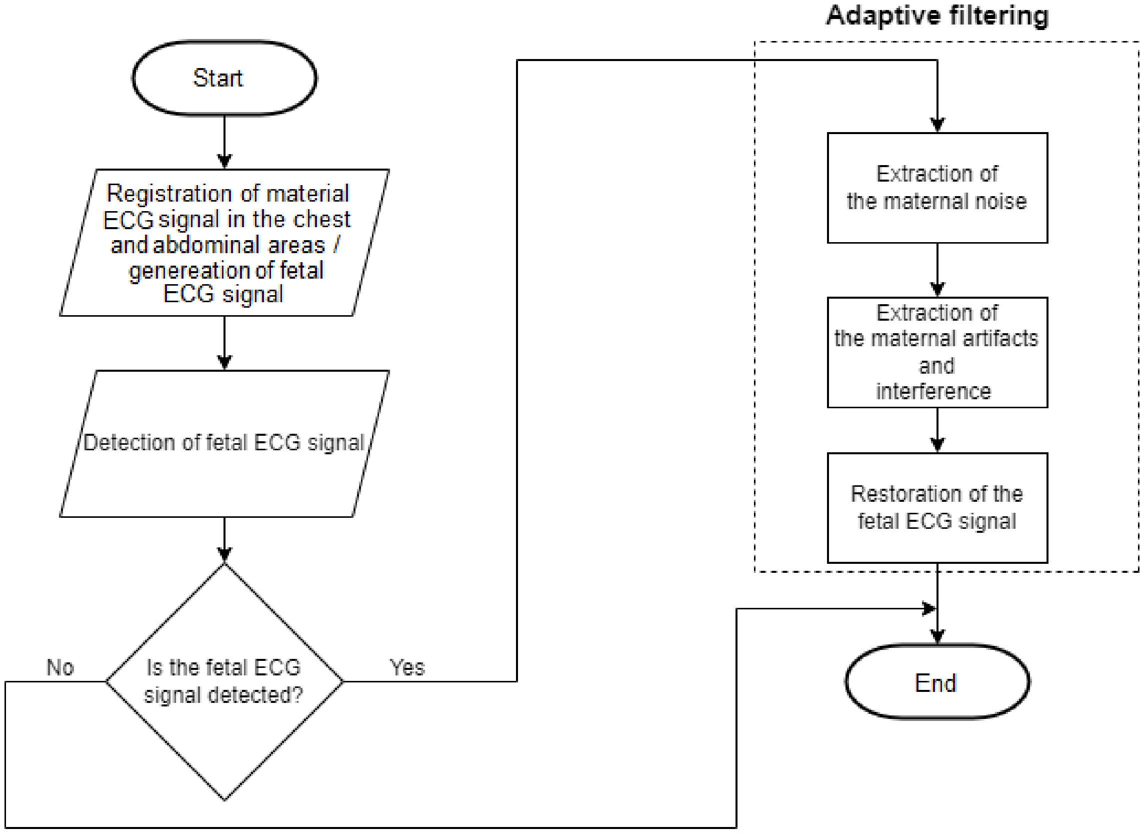

Figure 1: Algorithm for extracting fetal ECG signal [4]

The first step in the algorithm is the registration of maternal ECG signals in the chest and abdominal areas. The maternal ECG signals are recorded using non-invasive electrodes placed on the mother's chest and abdomen. The recorded signals are then filtered to remove any high-frequency noise and amplified to enhance the signal-to-noise ratio. The filtered and amplified signals are then used to identify the R-peaks, which are the most prominent features of the ECG waveform, using a peak detection algorithm.

The second step involves the detection of fetal ECG signals. This is accomplished by analyzing the morphological differences between the maternal and fetal ECG signals. Fetal ECG signals are typically weaker and have lower frequencies than maternal ECG signals. Therefore, fetal ECG signals can be detected by using a low-pass filter to remove high-frequency maternal noise and a high-pass filter to remove low-frequency noise.

If the fetal ECG signal is detected, the algorithm proceeds to the third step, which involves adaptive filtering. The adaptive filter removes maternal noise, artifacts, and interference from the recorded ECG signals, and enhances the fetal ECG signal. The adaptive filter is designed to adjust its filter coefficients in real-time based on the detected R-peaks of the maternal ECG signal.

The adaptive filter consists of three main components: the maternal component, the fetal component, and the noise component. The maternal component is estimated using a reference maternal ECG signal obtained from the chest or abdominal area. The fetal component is estimated by subtracting the maternal component from the recorded ECG signal. The noise component is estimated using a noise reference signal obtained from a noisy section of the recorded ECG signal.

The estimated maternal, fetal, and noise components are then used to update the filter coefficients of the adaptive filter in real-time. The updated filter coefficients are then used to filter the recorded ECG signal, thereby removing maternal noise, artifacts, and interference, and enhancing the fetal ECG signal.

Additionally, to verify the effectiveness of the proposed method, a generated ECG signal was used instead of a real signal. The generated signal was designed to simulate a typical fetal ECG signal and was added with varying levels of noise and artifacts to create a range of test signals. The algorithm was applied to each test signal, and the resulting output was compared to the original simulated fetal ECG signal. The results showed that the proposed method was effective in extracting the fetal ECG signal from the simulated noisy and artifact-containing signals.

3. Generation of fetal ECG signal

One way to generate a simulated fetal ECG signal is by using MATLAB, a popular programming language for signal processing and analysis. The first step is to define the parameters of the signal [13]. This includes setting the sampling frequency, duration of the signal, and fetal heart rate [14].

Sampling frequency refers to the number of samples taken per unit time. In this case, a sampling frequency of 1000 Hz was used, meaning that the signal was sampled 1000 times per second. The duration of the signal was set to 10 seconds, which is a typical length for ECG recordings. The fetal heart rate, which is the number of heart beats per minute, was set to 140 beats per minute, which is a common value for a healthy fetus is shown in Figure 2 [5].

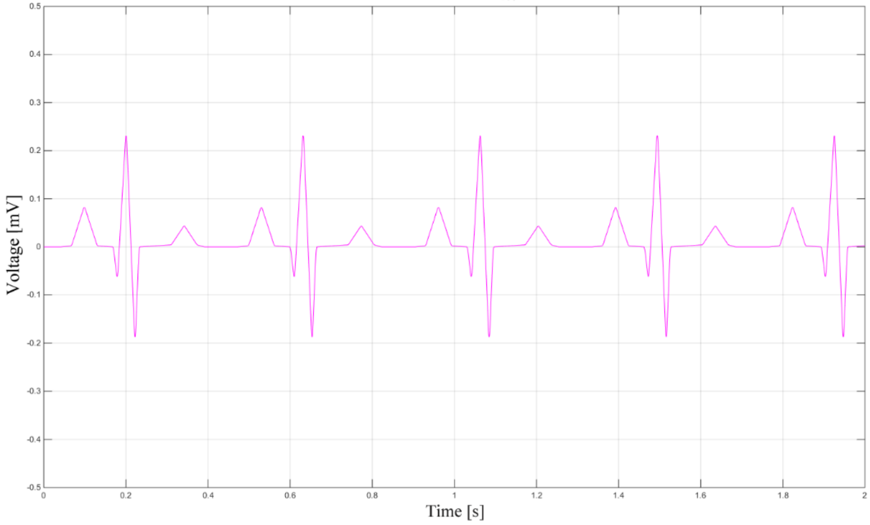

Figure 2: Generated fetus ECG signal

Next, a maternal ECG signal, which is shown in Figure 3, was generated using a mathematical model that simulates the electrical activity of the maternal heart. The simulated maternal ECG signal contains P, Q, R, S, and T waves, which correspond to different phases of the cardiac cycle.

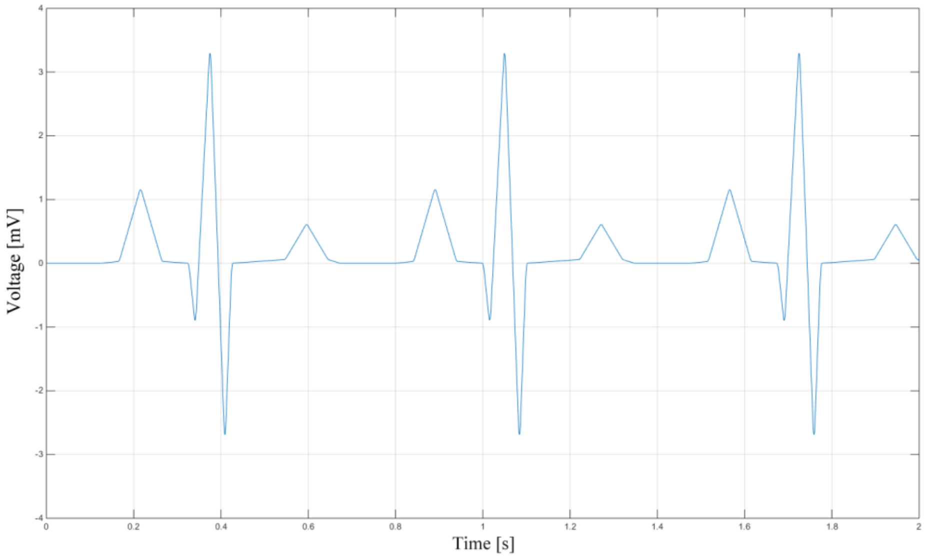

Figure 3: Generated maternal ECG signal

Once the maternal ECG signal is generated, a fetal ECG signal is generated by modulating it with a fetal heart rate signal. The fetal heart rate signal is modeled as a sinusoidal signal with a frequency that corresponds to the fetal heart rate. By multiplying the maternal ECG signal with a sinusoidal signal that corresponds to the fetal heart rate, a simulated fetal ECG signal is generated.

To simulate real-world conditions, noise is added to the simulated fetal ECG signal. The noise is modeled as a random signal with a specified power spectrum. In this case, white Gaussian noise with a signal-to-noise ratio (SNR) of 20 dB was added to simulate real-world noise conditions.

The addition of noise to the simulated fetal ECG signal is essential to create a more realistic signal that is similar to the noise present in actual fetal ECG recordings. The SNR of 20 dB is considered a reasonable value for fetal ECG recordings, as it allows for sufficient noise reduction while preserving the signal quality which is shown in Figure 4.

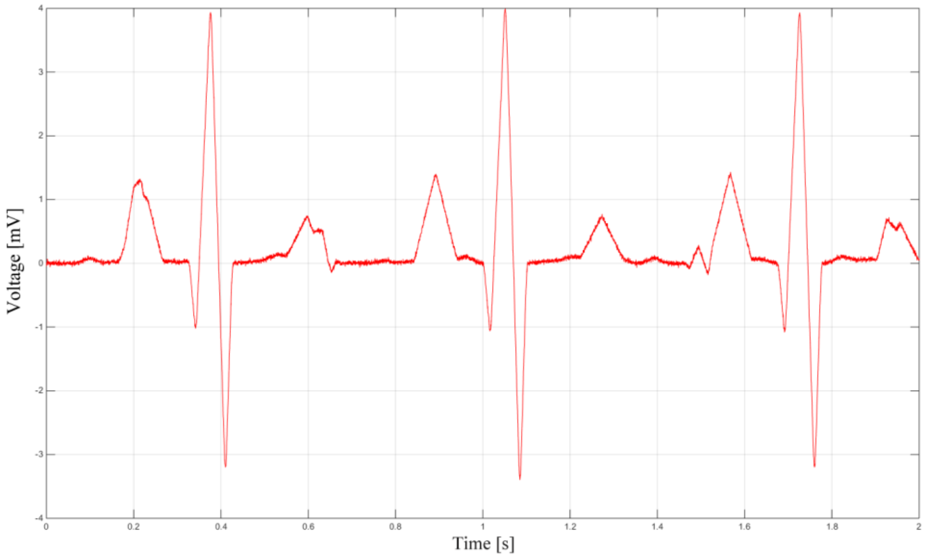

Figure 4: Generated fetal ECG signal with interference

4. Detection of fetal ECG signal

The fetal ECG signal in the mother's womb is both periodic (due to physical causes) and stochastic (due to the influence of different types of interference), which is why it is mathematically modeled as a periodically correlated stochastic process $\xi(t)$ [6, 8, 16]:

$$\xi(t) = \sum\nolimits_{k \in Z} \xi_k(t) e^{i^{2}\frac{\pi kt}{T}}, \ t \in \mathbf{R} \tag{1}$$

where $\xi_k(t), k \in \mathbf{Z}$ - stationary components (stochastic component) of the fetal ECG signal; $e^{i\frac{2\pi kt}{T}}$ - periodic component of the ECG signal with period T [9].

The representation of the mixture of fetal and maternal ECG signals as a periodically correlated stochastic process (statement 1) justifies the applicability of well-known statistical analysis methods (synphase, component) [11,12] for computing correlation components as indicators of fetal signal detection in the mixture, expressed as:

$$\hat{B}_k(u) = \frac{1}{T}\int_0^T \hat{b}_\xi(t,u) e^{-ik\frac{2\pi}{T}t} dt, \tag{2}$$

where $\hat{b}_\xi(t,u)$ - estimation of the parametric covariance of fetal ECG signal.

The correlation components of fetal ECG $\hat{B}_k(u)$ computed by the synphase method in the MATLAB environment are shown in Figure 5, which depict the presence of fetal ECG in the mixture with maternal and white noise signals as a periodically correlated stochastic process.

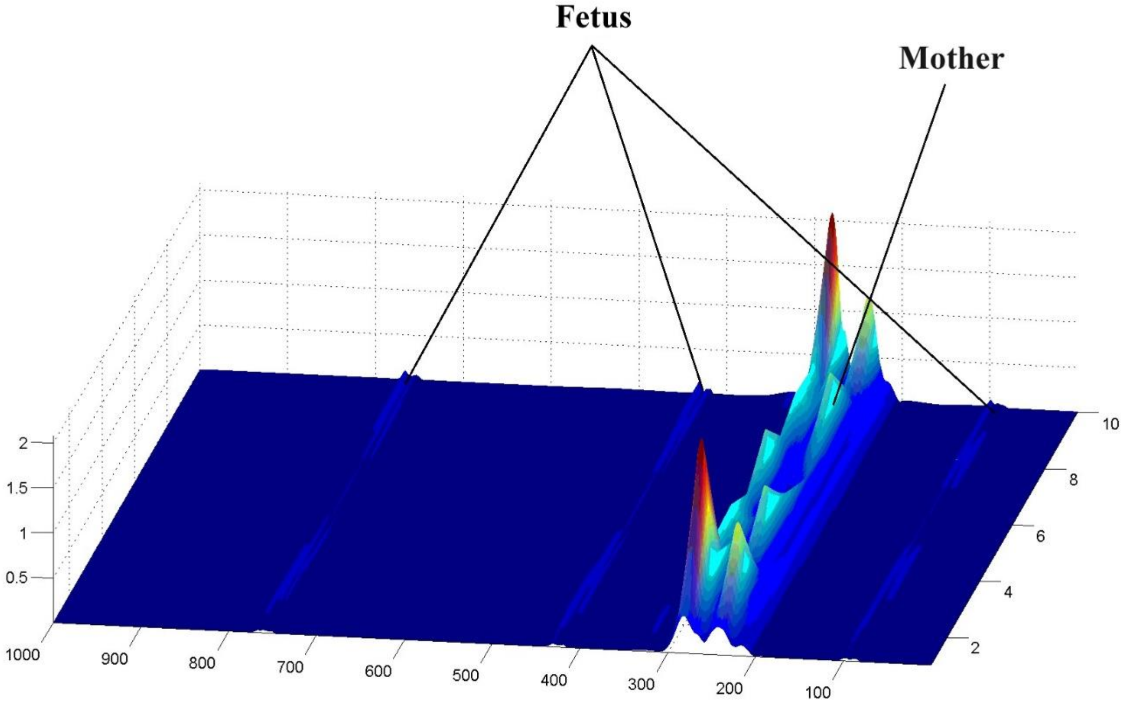

Figure 5: Correlation components of the mixture of fetal and maternal ECG signals (x-axis - shift, y-axis - component number, z-axis - power (mV^2))

Figure 5 shows that the fetal ECG components $\hat{B}_k(u)$ are concentrated within three shift ranges: 750-770, 420-440, and 85-105, whereas the maternal ECG components are within the range of 200-300, which quantitatively separates the components from each other and thus allows establishing the fact of the presence of fetal signals in the mother's uterus, which is important for prognostic diagnosis.

5. The adaptive filtering method for a mixture of fetal ECG signals

Adaptive filtering techniques are used to extract the fetal ECG signal from the mixture of signals that contain both the fetal and maternal ECG signals, as well as other potential noise artifacts. The adaptive filter coefficients are adjusted in real-time based on the characteristics of the input signals, allowing for effective separation of the desired fetal electrocardiogram signal from the interfering signals.

The adaptive filtering process typically involves several key steps. First, the adaptive filter is initialized with initial coefficients. Then, the input signals, which include both maternal and fetal electrocardiogram signals, are passed through the adaptive filter. The adaptive filter adjusts its coefficients based on the input signals, with the goal of minimizing the interference from the maternal electrocardiogram signal and other noise artifacts, while preserving the fetal electrocardiogram signal.

The adjustment of filter coefficients is done iteratively based on a chosen adaptation algorithm, which can vary depending on the specific application and requirements. Commonly used algorithms include the least mean squares (LMS) algorithm, normalized least mean squares (NLMS) algorithm, recursive least squares (RLS) algorithm, and others. These algorithms adapt the filter coefficients in real-time based on the difference between the filtered output and the desired fetal electrocardiogram signal.

The adaptive filter continues to update its coefficients as new input signals are processed, allowing it to adapt to changes in the signal characteristics over time. This adaptability makes adaptive filtering well-suited for addressing the challenges associated with the amplitude difference between fetal and maternal signals, as well as other potential interference in the signal.

In addition to adaptive filtering, another technique that may be used in conjunction with adaptive filtering is the addition of uncorrelated Gaussian noise to the input signal. This noise can help eliminate or reduce the impact of broadband interference on the extracted fetal electrocardiogram signal, further improving the accuracy and reliability of the diagnostic results.

The structure of adaptive filtering for the selection of fetal ECG signal and removal of maternal heartbeat in a mixture of signals can be visualized in Figure 6, which typically shows the input signals, the adaptive filter, and the filtered output. This visual representation helps illustrate the process of adaptive filtering and how it can effectively extract the fetal ECG signal from the mixture of signals.

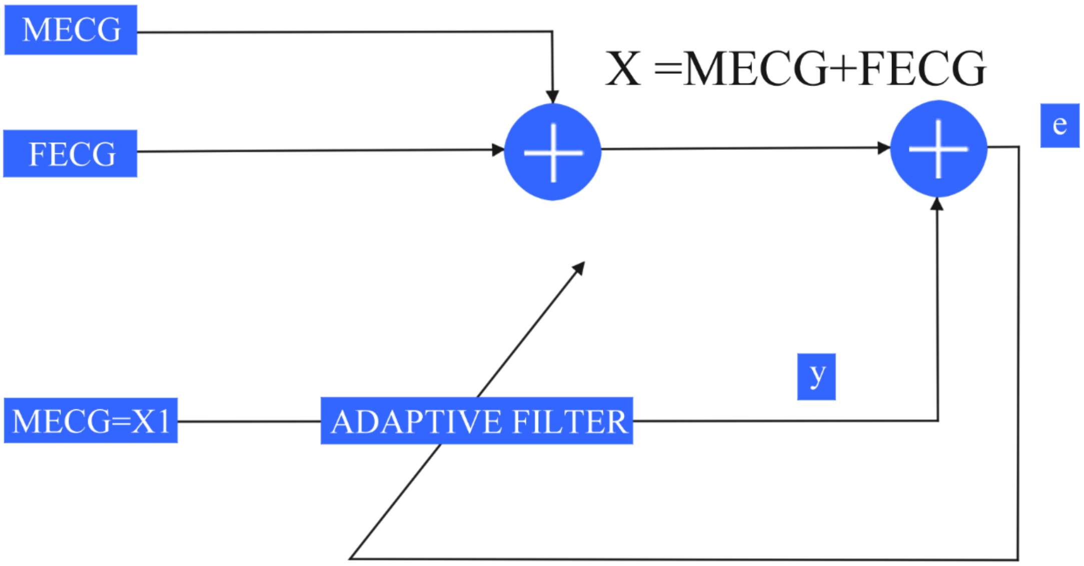

Figure 6: Adaptive filter

The third part of the process involves using digital filters, such as Finite Impulse Response (FIR) and Infinite Impulse Response (IIR), for high-frequency output in digital signal processing (DSP). FIR filters have the advantage of easily designing a linear phase and can provide computational efficiency by omitting some calculations.

To calculate the fetal heart rate, the R-peaks of the FECG signal must be extracted. An FIR filter with appropriate filter coefficients is used to remove the high frequency, and a threshold value is set to detect peaks with higher values than the threshold as R-peaks of the FECG signal. Finally, the fetal heartbeat is calculated from the R-R interval by counting the number of R-peaks [15].

6. Results

To calculate the fetal heart rate from the fetal ECG signal (FECG), a fixed duration of time is observed and the number of beats is calculated. This is done by identifying the R-peaks in the FEKG signal, which correspond to the contraction of the fetal heart muscles. Each R-peak represents one heartbeat. Filtered fetal ECG signal is shown in Figure 7.

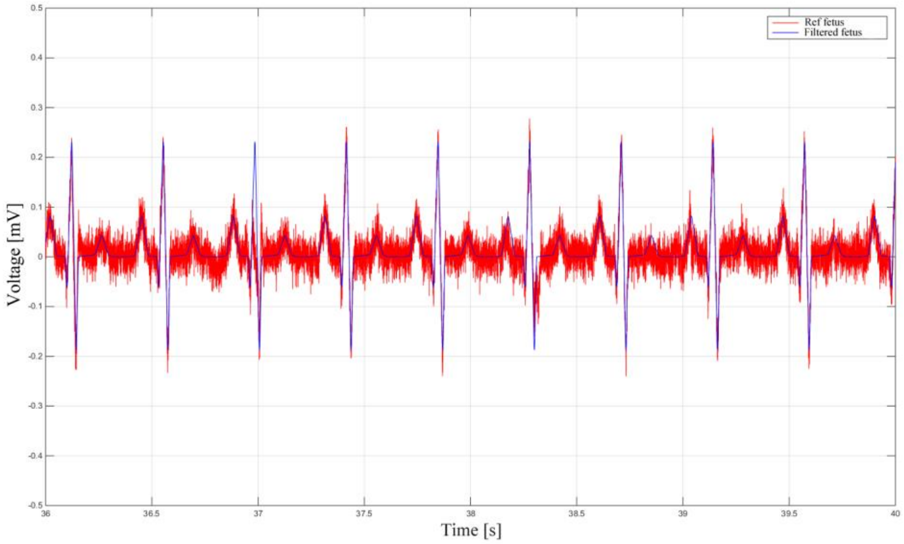

Figure 7: Filtered fetal ECG signal

Before counting the R-peaks, the FEKG signal is preprocessed to remove noise and artifacts. This involves applying filters to remove unwanted frequencies and using adaptive noise canceling (ANC) to remove the maternal heart rate from the FEKG signal. The preprocessed signal is then cleaned and thresholded so that any value above the threshold is considered a peak.

The QRS detection methods discussed earlier are used to identify R-peaks in the FECG signal. The most optimized method is to detect the R-peaks directly from the FECG signal. The R-peaks are identified as the highest points in the QRS complex, which corresponds to the depolarization and repolarization of the fetal heart muscles.

The number of R-peaks is counted within the fixed duration of time, and the fetal heart rate is calculated by multiplying the number of R-peaks by a factor that represents the number of beats per minute. In this case, the heart rate was found to be 135 beats per minute, which falls within the normal range of fetal heart rates of 120 to 160 beats per minute.

Finally, the FECG signal is plotted along with the R-peaks to visualize the fetal heart rate. The resulting graphs show the waveforms of the FECG signal with clear peaks corresponding to the fetal heartbeats. These graphs can be used for further analysis and diagnosis of fetal health. Figure 8 illustrates the use of peak detection for visualizing the fetal heart rate.

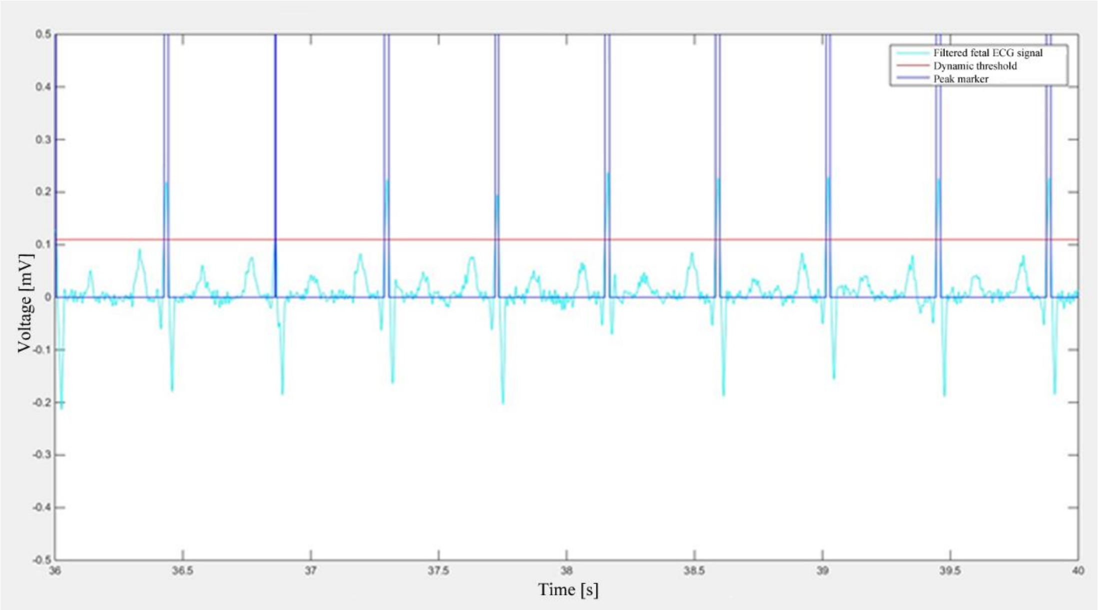

Figure 8: Peak detection for visualizing the fetal heart rate

Peak detection is an important tool for fetal heart rate monitoring, as it can help identify potential problems such as fetal distress or abnormal heart rate patterns.

7. Conclusions

In conclusion, the accurate detection of fetal distress during pregnancy is essential for reducing the risk of adverse outcomes and ensuring the health of both the mother and the future child. Non-invasive methods for fetal monitoring, such as fetal cardiodiagnostic systems, are commonly used to record the fetal ECG signal, which is a combination of useful fetal and maternal ECG signals. However, selecting a reliable fetal ECG signal can be challenging due to weak signals and interference.

Various methods, such as blind signal separation, adaptive filtering, synchronous method, component method, spectral method, and bispectral processing, have been developed for extracting useful fetal ECG signals from a mixture of signals. However, the limitations of the existing methods have made it necessary to develop a new method that can consider time-frequency characteristics and phase-time parameters of the ECG signal simultaneously to provide more reliable results.

The proposed algorithm for fetal ECG extraction involves several steps, including maternal ECG signal registration, fetal ECG signal detection, and adaptive filtering. The adaptive filter removes maternal noise, artifacts, and interference from the recorded ECG signals and enhances the fetal ECG signal in real-time based on the detected R-peaks of the maternal ECG signal. The effectiveness of the proposed method was verified using simulated noisy and artifact-containing signals.

The development of a reliable and accurate method for fetal ECG extraction is crucial for the timely detection of fetal distress and the prevention of adverse outcomes. Future research in this area should focus on further refining and improving the proposed algorithm, as well as exploring new methods for fetal monitoring and diagnosis. Ultimately, the goal is to ensure the best possible outcomes for both mother and future child.

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