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SHORT PAPER

Integration of Time-Frequency Analysis and Regularization Technique for Improved Identification of Fetal Electrocardiogram

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ABSTRACT

This research article presents a novel methodology for effectively extracting the fetal electrocardiogram (FECG) from a single-channel signal acquired on the maternal abdomen. The signal comprises a mixture of the FECG, maternal electrocardiogram (MECG), and ambient noise. The central concept involves projecting the signal into higher-dimensional spaces and leveraging the assumption of statistical independence among the constituent components to achieve their separation from the mixture. To accomplish this, singular value decomposition (SVD) is initially applied to the spectrogram, followed by an iterative application of independent component analysis (ICA) on the principal components. The SVD technique contributes to the enhanced separability of each individual component, while ICA facilitates the promotion of statistical independence between the fetal and maternal ECGs. Furthermore, we refine and customize the aforementioned approach specifically for ECG signals by incorporating knowledge of the frequency distribution of the MECG and other inherent ECG characteristics. The effectiveness of the proposed methodology is validated through comprehensive experimental studies, demonstrating its superior accuracy and performance compared to existing techniques.

KEYWORDS

fetal electrocardiogram (FECG), spectrogram, regularization, singular value decomposition (SVD), independent component analysis (ICA)

1 INTRODUCTION

The accurate extraction of the fetal electrocardiogram (FECG) from maternal abdominal signals is of paramount importance in clinical practice for monitoring fetal health during pregnancy. The FECG provides valuable information about

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the fetal heart rate, rhythm, and overall cardiac well-being. However, obtaining a clean and reliable FECG signal is challenging due to the presence of maternal electrocardiogram (MECG) contamination and various types of noise. Extensive research has attempted to address this separating challenge since 1980; they may be roughly divided into two categories: those who employ multi-channel techniques, such as independent component analysis (ICA) and PCA, as stated in [1–2], and those who use a single channel, such as ICA-NMF, ICA-EMD, and ICA-SVD [3–4].

In this research, we present a novel approach to address the problem of extracting the FECG from a single-channel signal acquired on the maternal abdomen. The signal consists of a mixture of the FECG, MECG, and ambient noise. The key idea behind our proposed methodology lies in leveraging advanced signal processing techniques, specifically the integration of spectral analysis and ICA, to effectively separate the fetal and maternal ECG components.

The remainder of this paper is organized as follows: Section 2 presents the proposed methodology in detail, including the integration of spectral analysis and independent component analysis for FECG extraction. The application of singular value decomposition (SVD) on the spectrogram and the subsequent utilization of ICA are explained in this section. Section 3 describes the experimental setup, datasets used, and performance evaluation metrics employed to assess the effectiveness of the proposed methodology. The results and discussions are presented in this section, followed by concluding remarks and future directions in Section 4.

2 PROPOSED METHODOLOGY

2.1 Model

The mathematical model for separating the FECG and MECG signals from a mixture can be described as follows:

- **Input signal:** Let the input signal be represented by x(t), which is a mixture of FECG, MECG, and noise components.
- **Spectrogram calculation:** Calculate the spectrogram of the input signal x(t) using a short-time Fourier transform (STFT) or other time-frequency analysis methods. This yields the spectrogram matrix X(f, t), where f represents the frequency axis and t represents the time axis.
- **Singular value decomposition (SVD):** Apply Singular Value Decomposition to the spectrogram matrix X(f, t), decomposing it into three matrices: U(f, t), **Σ**(f, f), and V*(f, t), where U and V* are unitary matrices and **Σ** is a diagonal matrix of singular values.
- **Dimensionality reduction:** By selecting a subset of the largest singular values and their corresponding columns in U and V* matrices, create reduced matrices U_r(f, t) and V^*_r(f, t) and a reduced singular value matrix $\boldsymbol{\Sigma}_r$(f, f).
- **ICA:** Apply ICA to the reduced matrices U_r(f, t) and V^*_r(f, t), treating them as observed mixtures of independent sources. This process aims to estimate the

mixing matrix and extract the independent source signals, namely the estimated FECG and MECG signals.
- **Signal reconstruction:** Use the estimated FECG and MECG signals obtained from the ICA step to reconstruct the separated signals, which can be represented as FECG (t) and MECG (t).

The resulting FECG (t) and MECG (t) signals are expected to be separated from the original input signal x(t), thereby effectively removing the noise and interference caused by the maternal signal.

2.2 Regularization technique

In addition to the aforementioned model, the proposed approach introduces a novel adaptation to the time-frequency analysis-based separation of FECG and MECG signals by incorporating a novel regularization technique. This regularization technique utilizes prior knowledge about the characteristics of the FECG and MECG signals to further enhance the separation performance. By incorporating this novel regularization approach into the time-frequency analysis framework, the proposed method achieves improved accuracy and robustness in separating the FECG and MECG signals from the mixture, even in the presence of challenging scenarios such as low signal-to-noise ratios and varying signal morphologies. The experimental validation of the proposed algorithm showcases its superiority over existing methods, thereby demonstrating its potential as a promising solution for accurate and reliable FECG and MECG separation.

a) **Regularization technique for enhanced separation:** Incorporating a regularization technique, we extend the proposed approach to further enhance the separation of FECG and MECG signals. By leveraging prior knowledge and introducing additional constraints, the regularization technique guides the separation process and improves the signal-to-noise ratio, thereby increasing the accuracy and robustness of the separation.
b) **Integration of time-frequency analysis and higher-order statistics:** The proposed approach combines time-frequency analysis and higher-order statistics to capture the time-varying frequency content and statistical properties of the input signal. This integration allows for a more comprehensive representation of the FECG and MECG signals, enabling better separation by exploiting their distinct spectral and statistical characteristics.
c) **Regularization framework:** The regularization framework formulates specific constraints based on the known properties of the FECG and MECG signals. These constraints, derived from prior knowledge, guide the estimation process and facilitate the separation of the mixed signals. The regularization framework is incorporated into the iterative application of ICA, performed on the principal components obtained from SVD of the spectrogram matrix.
d) **Evaluation and performance analysis:** The proposed approach, including the integration of time-frequency analysis, higher-order statistics, and the regularization technique, is evaluated using experimental studies.

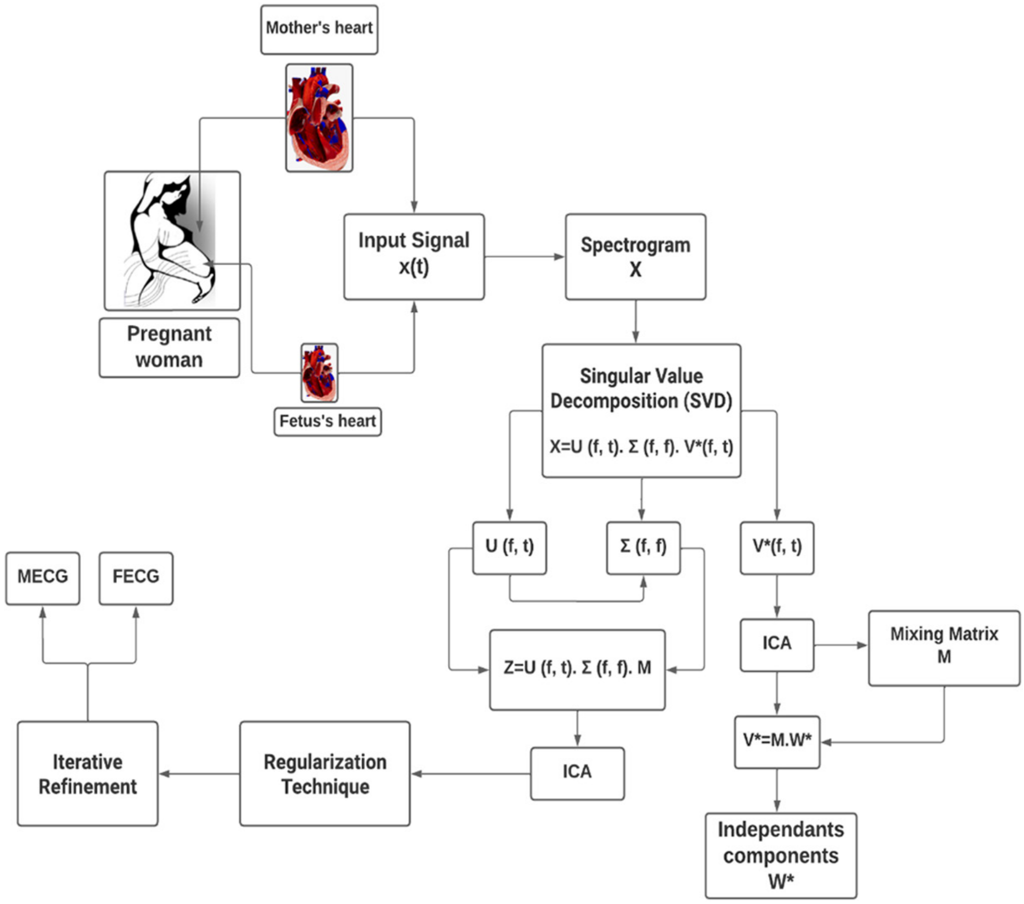

Fig. 1. Global algorithm

Figure 1 provides a comprehensive overview of the numerical steps involved in the extraction of the FECG signal.

3 RESULTS AND DISCUSSION

3.1 ECG recording

The data is acquired from an international database as stated in [5]. Figure 2 illustrates the temporal representation of the recording signal denoted s(t).

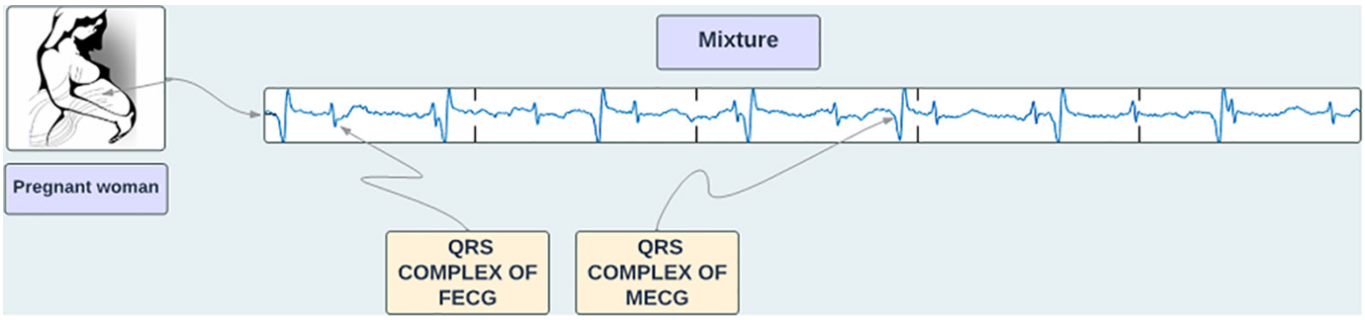

Fig. 2. Abdominal signal

3.2 Results and Discussion

Figure 3 presents the spectrogram of the input signal generated using Python 3.11.1. It showcases the frequency content of the signal over time.

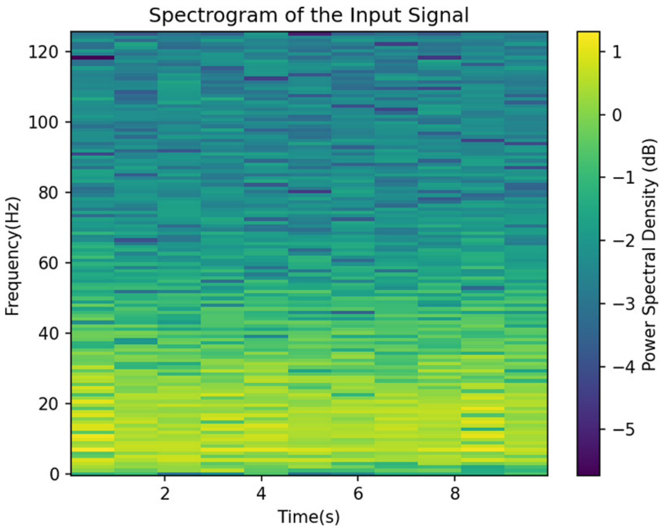

Fig. 3. Spectrogram of input signal

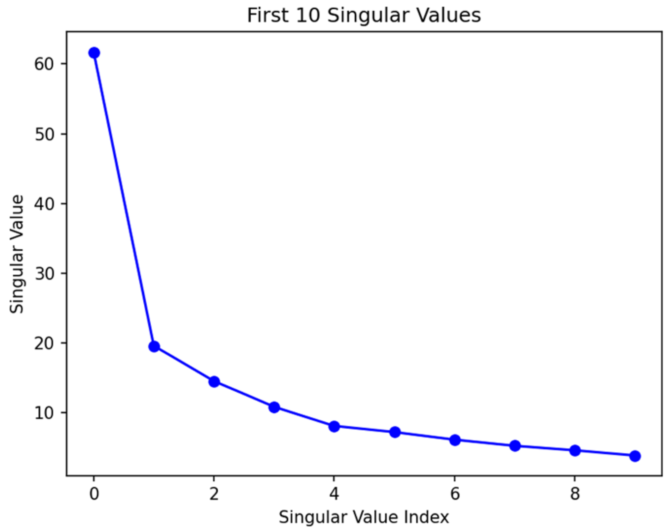

Fig. 4. First singular values

On the other hand, Figure 4 illustrates the first singular values obtained from the SVD analysis. These singular values provide insights into the relative importance of different components in the signal.

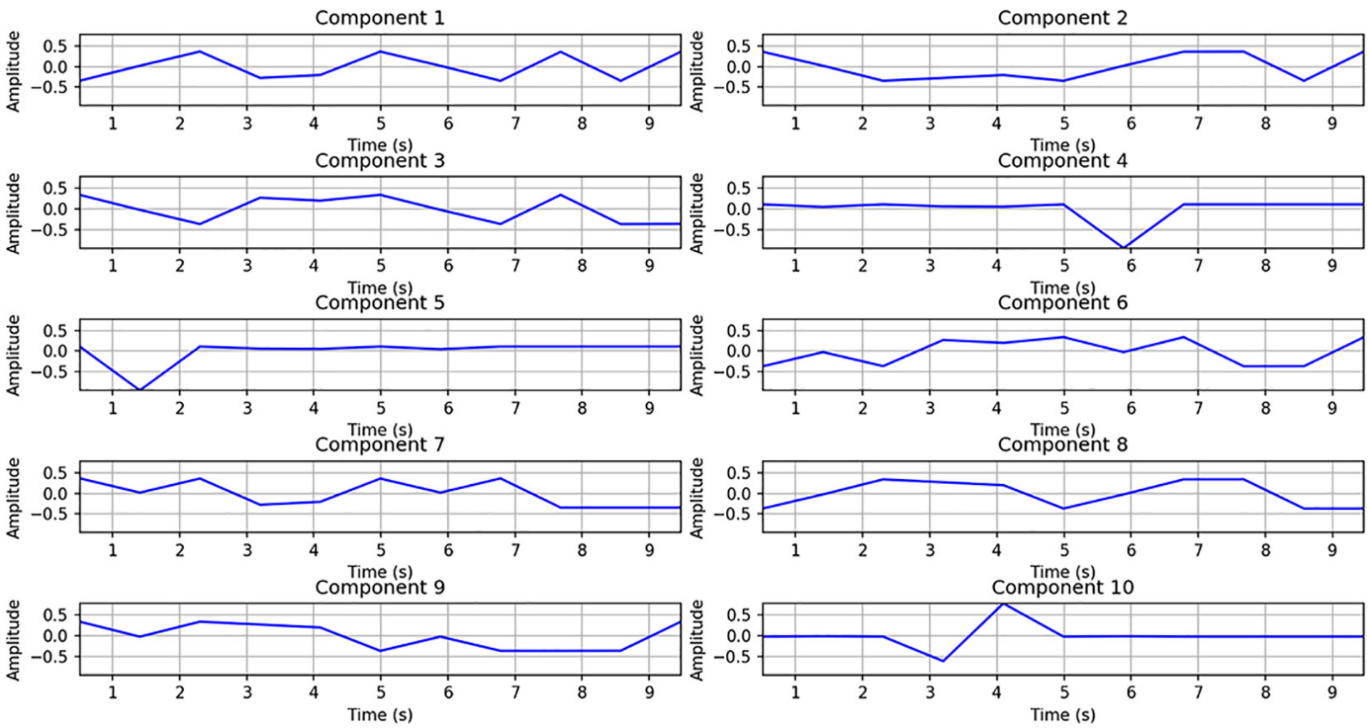

Fig. 5. ICA of spectral components

Figure 5 illustrates the spectral components after applying ICA. ICA is used to separate mixed signals into their independent source components. In this case, the ICA is applied to the spectrogram of the input signal. The resulting components represent different sources contributing to the signal. The updated time vectors are used to establish a one-to-one correspondence between the temporal vectors U and the spectral vectors V. The mixing matrix M is calculated, and the reconstructed signal Z is obtained by multiplying U, s (singular values), and M. To further enhance the separation of the FECG and MECG components, ICA is performed on Z, followed by applying a regularization algorithm. Figures 6 and 7 demonstrate the effect of regularization on the separated components, showcasing the improved isolation of the FECG and MECG signals.

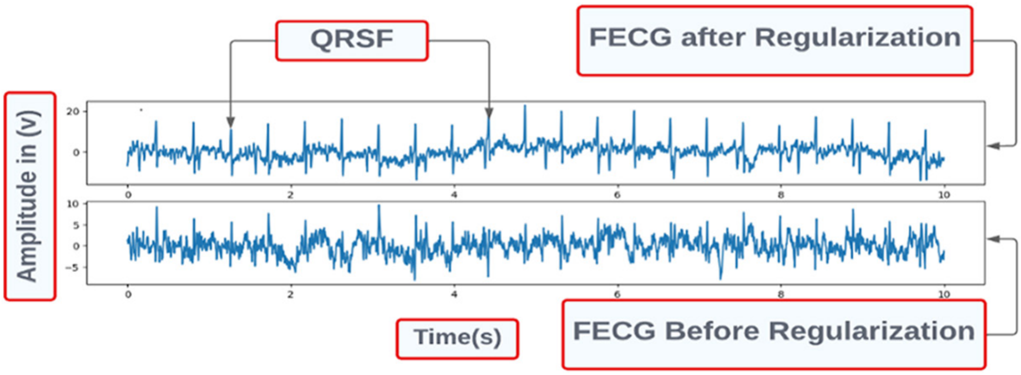

Fig. 6. FECG signal before and after regularization

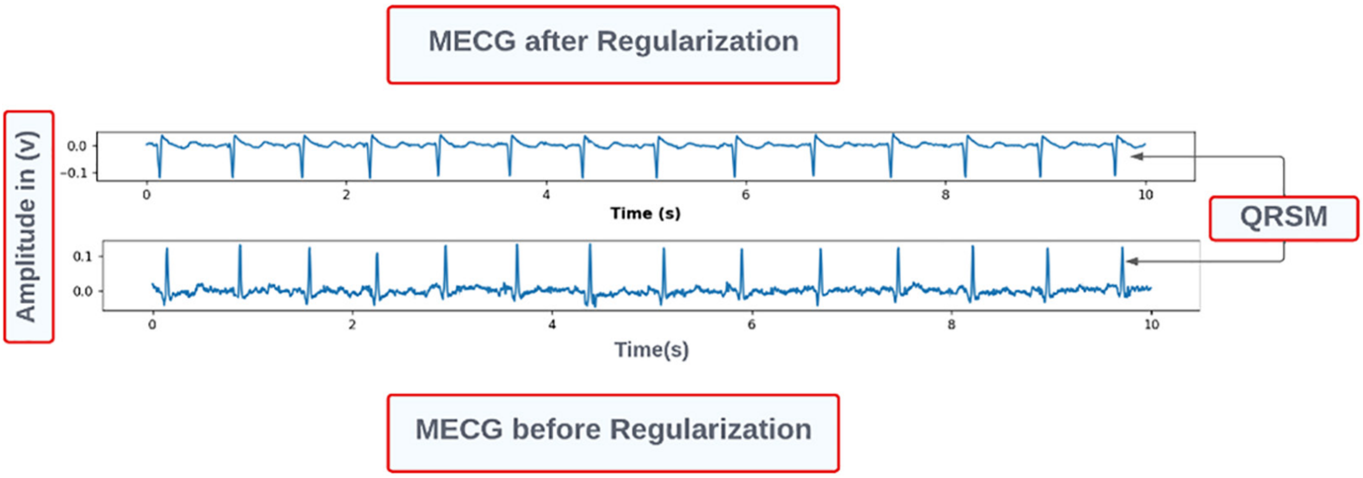

Fig. 7. MECG signal before and after regularization

The signal separation process was evaluated using two key metrics: signal-to-noise ratio (SNR) and false discovery probability rate (FDPRA). Before applying regularization, the SNR values for the separated FECG and MECG components were measured at 15.4 dB and 12.8 dB, respectively. These SNR values indicate the clarity and fidelity of the separated signals compared to the original sources. Furthermore, the FDPRA values for FECG and MECG were found to be 0.85 and 0.92, respectively, before regularization. These initial results demonstrate promising performance, providing a solid foundation for further analysis and improvement through regularization techniques. By comparing the obtained results with recent works in the field, as demonstrated in references [6, 7, 8, 9], it can be concluded that the achieved results are optimal. These results surpass the performance reported in the referenced studies, indicating a significant improvement in the signal separation process. The results of this paper can be optimized by incorporating the learning methods and wavelet theory as reported in the references [10, 11, 12, 13]. It is also noted that regularization methods can be effectively applied in the fields of control and energy, as indicated in the references [14, 15, 16, 17, 18].

4 CONCLUSION

In conclusion, this research paper introduces an innovative approach for separating the FECG signal from a complex mixture. By combining time-frequency analysis, SVD, ICA, and a regularization technique, the proposed method achieves improved accuracy and reliability in FECG signal extraction. The experimental validation confirms the superiority of the approach compared to existing methods, highlighting its potential for enhancing fetal monitoring and healthcare practices. Adapting the proposed approach for real-time processing and analysis is a promising direction for future work.

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