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Swarm Decomposition of Abdominal Signals for Non-invasive Fetal ECG Extraction*

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***Abstract*—The non-invasive fetal electrocardiography (fECG) extraction from maternal abdominal signals is one of the most promising modern fetal monitoring techniques. However, the non-invasive fECG signal is heavily contaminated with noise and overlaps with other prominent signals like the maternal ECG. In this work we propose a novel approach in non-invasive fECG extraction using the swarm decomposition (SWD) to isolate the fetal components from the abdominal signal. Accompanied with the use of higher-order statistics (HOS) for R peak detection, the application of the proposed method to the Abdominal and Direct Fetal ECG PhysioNet Database resulted in fetal R peak detection sensitivity of 99.8% and a positive predictability of 99.8%. Our results demonstrate the applicability of SWD and its potentiality in extracting fECG of good morphological quality with more deep decomposition levels, in order to connect the extracted structural characteristics of the fECG with the health status of the fetus.**

***Clinical Relevance*— The developed method shows improvement in fetal R peak detection for certain signals.**

I. Introduction

Fetal monitoring during pregnancy relies on the analysis of the fetal heart activity, mainly the fetal heart rate (FHR). The FHR is crucial for identifying factors that may affect the health of the fetus, cause intrauterine death, or lead to permanent damage to the fetus [1], and it became the standard clinical practice in fetal monitoring. The most accurate FHR measurement method is the direct Fetal Electrocardiogram (fECG)[2]. Another method for FHR monitoring is cardiotocography (CTG)[1], which is based on doppler ultrasound (US). Doppler US became a standard method since 1970s, however, it provides lower accuracy measurement of the fetal cardiac cycle as compared to fECG [3]. fECG is measured either invasively (direct fECG), using the transvaginal fetal scalp electrodes, or non-invasively, by means of electrodes placed on the mother's abdomen[1]. The invasive approach provides accurate recording with less processing due to the direct contact of the electrode with the fetal head, however, it risks causing complications such as an infection to the mother or fetus. The non-invasive (NI-fECG) approach is much more comfortable for the mother and the fetus, is of negligible risk, and can be used for perinatal and intrapartum checks [4].

In NI-fECG, the desired fECG is extracted from the maternal abdominal Electrogram (abEG). The AbEG is a mixture of signals generated by multiple sources such as maternal electrocardiogram (mECG), maternal muscles, and fetal heart, contaminated by noise (electrostatic potentials, network interference, etc.) and passed through dielectric biological media [5]. Linear phase filter can be used to remove the low frequency uterus activity and a notch filter can be used to remove the power line interface. However, the mECG and fECG overlap in amplitude and frequency response characteristics making their isolation quite challenging. In addition to the signal spectra overlap, the amplitude of the fECG is less than 1/50 of the mECG, 5-20 μV and 1000 μV respectively [6].

Many algorithms have been proposed to extract fECG from the abEG signal like blind source separation (BSS), and wavelet-based techniques[1]. The BSS technique assumes that the maternal and fetal signals, source signals, exist independently. It constructs a transformation matrix to separate maternal and fetal complexes, from the abdominal signal by maximizing each source's statistical independence. However, mECG and fECG are non-stationary signals; hence many electrodes should be involved to provide a better result using BSS. However, this is unpleasant and often impractical for pregnant women especially in labor. Wavelet-transform methods offer variable time-frequency resolution and are effective with non-stationary signals. Khamene at al. [7] removed mECG from abdominal signals and used wavelet transform to identify fECG complexes. Wavelet transform methods technique proved to be suitable for advanced preprocessing of abdominal signals, and for partially suppressing the maternal component allowing for fetal R peak detection but any further morphological analysis is not possible.

In this paper we present a novel method to extract the fECG signals from abdominal recordings. This method is based on the attenuation of the mECG using swam intelligence decomposition of non-stationary signals; namely the swarm decomposition (SWD)[8]. The SWD is based on parameterizing swarm filter (SwF) to decompose the multi-component input

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signal, abEG, into oscillatory components (OCs). The fECG signal is extracted by removing the mECG OCs from the abEG. The algorithm is evaluated by the quality of extracted fECG R peak locations against direct scalp fECG. There is a need to explore new signal processing techniques for fECG extraction in a way that can conserve some of the morphology of the signal with a smaller number of channels.

II. METHODOLOGY

A. Description of the Data

The algorithm was implemented on the Abdominal and Direct Fetal Electrocardiogram database from the PhysioNet repository [9]. The database consists of 5 abdominal datasets from 5 women of gestational ages 38-41 weeks sampled at 1kHz. Each dataset has recordings of length 300 seconds from 4 electrodes placed around the umbilicus with the 5th electrode directly from the fetal scalp, acting as the gold standard for fetal QRS (fQRS) location, as seen in Figure 1. The algorithm ran using MATLAB R2020b. Detected fetal R peak locations were compared to the carefully annotated reference QRS locations (gold standard). The proposed method has five main steps which are summarized in Figure 2, and explained in detail in the next sections.

B. Pre-processing

The abdominal signal is contaminated with noise from maternal respiration, maternal and fetal movements, uterine contractions, and surrounding interference. To reduce the noise and correct baseline wander, the raw abdominal signal is passed through a digital Butterworth filter with cutoff frequencies 3-80Hz for low and high-frequency noises. The power line signal is removed by a notch filter at 50 Hz. Finally, the abdominal signal is smoothed, normalized and zero mean. The raw abdominal signal and pre-processed signal can be seen in Figure 2 (A) and (B) respectively.

C. Maternal ECG attenuation

The filtered abdominal signal contains mECG, fECG and some noise. SWD is used to decompose the multi-component abdominal signal into OCs, each of which is the result of an iterative application of SwF. The SwF parameters: P_{th} ,which controls how fine or coarse the decomposition is, and StD_{th}, which determines the termination of the iterative SwF if

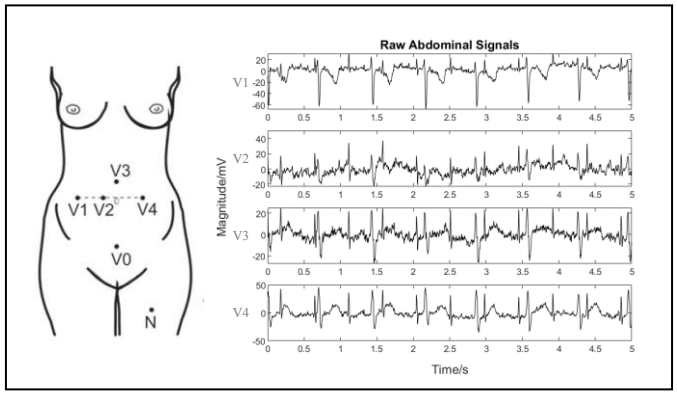

Figure 1: On the left: electrode placement system for the PhysioNet dataset. On the right: raw acquired abdominal signals

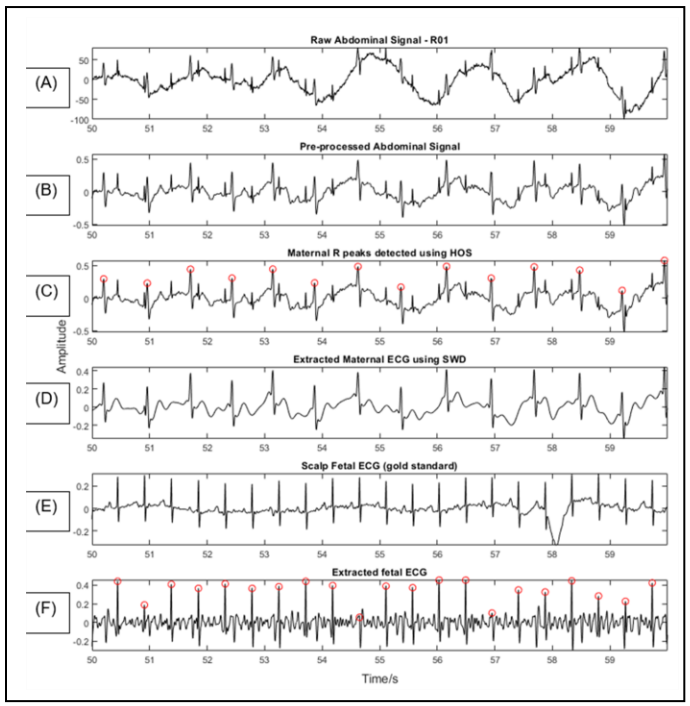

Figure 2: The process representing the proposed algorithm for fECG extraction from abdominal signal; (A) the abdominal signal, (B) preprocessed and normalized signal, (C) maternal R peak detection in red circles, (D) the extracted maternal signal after swarm decomposition with clear exemption of fetal QRS complex, (E)scalp fECG signal (gold standard), (F) extracted fECG with R peaks detected using higher-order statistics method shown in red circles.

deviation threshold between iterations is less than it, are set at 0.1 and 0.05 respectively. A coarse or fine SWD refers to the number of components that will be extracted, a larger value of P_{th} means a more coarser decomposition, i.e., a smaller number of components while a smaller value of P_{th} means more fine decomposition and more components. These filter parameters yield an average of 8 components, OCs, for our abdominal signals.

In Figure 3 (A) and (B), we can see a part of the original signal and its frequency decomposition respectively. In Figure 3 (C) we observe the 4 mono-component signals extracted via SWD; where the first 7 components span the 0-15 Hz range and the 8th component spans mainly the 15-30 Hz range. The mECG and fECG exist across all these frequency ranges, however, the fQRS is in the 6-15 Hz [1], therefore, all components with a frequency mean below 7 Hz are considered maternal components. The maternal QRS (mQRS) is found in 0.5-35 Hz [1], therefore for all components with a frequency mean above 7 Hz we need to extract the maternal signal, specifically the mQRS. In order to ensure a good separation in the overlapped components a binary mask is applied on the components around the mQRS with a value of 1 at the mQRS part and decaying into 0 elsewhere. The mQRS complex is detected using the Higher-Order Statistics (HOS) R-wave detection method proposed in the work of Panoulas et al. [10]. The method implements an adaptive R peaks detector by applying HOS-based parameters, skewness and kurtosis. This method exhibits over 99% sensitivity when applied to the Massachusetts Institute of Technology/Beth Isreal Hospital (MIT/BIH) ECG database. To

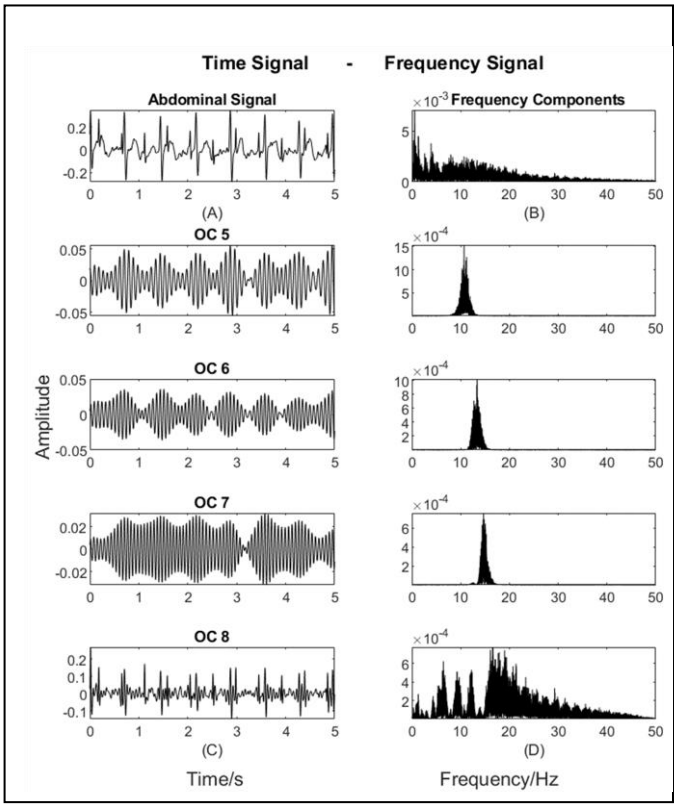

Figure 3: Abdominal signal in (A) time and (B) frequency domain. The extracted oscillatory components 5 to 8 using SWD are shown in (C) and (D) in time and frequency domain, respectively.

overcome poor maternal R peak detection quality in some channels we consider that the maternal R peaks have the same timestamp across all channels and the channel with the best detected maternal R peaks (highest number of peaks within the normal heart rate and with the least standard deviation in magnitude) becomes the reference for other channels. The binary mask boundaries are set to 40ms before and 60ms after the R peak. These boundaries are based on the knowledge that the average adult QRS complex is 100ms and a non-pathological Q-wave does not exceed 40ms [11]. After applying the mask on components with frequency > 7 Hz, the conserved maternal components are added to the maternal components of frequency < 7 Hz. The final maternal signal can be represented as follows:

$$mECG = \sum_{1}^{k} OC(k) + \sum_{k+1}^{N} OC(k) \times M_{binary} \qquad (1)$$

where k is the number of OCs below 7 Hz, N is the total number of OCs, and M_{binary} is the binary mask. As seen in Figure 2 (D), the extracted maternal is visually of good quality and the fetal R peaks are clearly excluded.

D. Fetal R Peaks Detection

After eliminating the mECG signal, this leaves behind the fECG and minimal noise. As can be seen in Figure 2 (F), the fetal R peaks are detected from the extracted fECG using the HOS R wave detector function mentioned earlier with the fetal flag [10]. In most abdominal signals the fetal R peaks have very low magnitude and require extracted fECG for detection.

E. Performance Evaluation

In addition to the visual evaluation of the results, the correctly detected QRS complexes are quantitatively evaluated by the sensitivity, Se, and the positive predictive value PPV as follows:

$$Se\ (\%) = \left(\frac{TP}{TP + FN}\right) \times 100 \qquad (2)$$

$$PPV\ (\%) = \left(\frac{TP}{TP + FP}\right) \times 100 \qquad (3)$$

TP (True Positive) is the number of correctly detected fQRS complexes, FN (False Negative) is the number of undetected QRS complexes, and FP (False Positives) is the number of falsely detected QRS complexes.

III. Results

Figure 2 shows the result of one channel from dataset R01 of the PhysioNet database mentioned earlier. It can be noted that the position of the fetal R peaks through the signals are connected and that in the extracted signal all fetal R peaks were detected. The analytical results of correct number of fetal R peak detections by the proposed algorithm are shown in Table i, and prove the efficiency and potentiality of the novel fetal extraction algorithm. The algorithm achieved a sensitivity of up to 99.8% which outperformed the highest sensitivity of 99.7% in other developed methods applied on the same database in the work by Jezewski et al. [9]. Additionally, it is giving better results than the hybrid methods utilizing EMD such as EMD-WT [12].This algorithm works on single channel data or multi-channel data (in the sense of utilizing the best fetal R peak detected between different channels). Figure 4 shows the that the instantaneous FHR calculated from the extracted fECG was very similar to the FHR calculated from the direct fECG. This illustrates the very good correlation between the two RR interval measurements. To further detail the correlation Figure 5 shows the Bland-Altman plot of the direct fECG from scalp and the extracted fECG RR intervals of over 2500 intervals of the five recordings data set after SWD. The mean value of vertical axis is 0.56 with a standard deviation of 16.23. The lower and upper limit are at -31 and +32ms respectively. The spearman rank correlation between mean and difference, denoted as r_s in the figure, is of value 0.19 (p<0.001).

IV. Discussion and Conclusion

The results presented in this study confirm that the novel SWD fECG extraction method is a highly effective method in extracting mECG, fECG and fetal R peak detection. Unlike other techniques like BSS which assume stationary signal, the SWD applies non-stationary multi-component signal decomposition. The results in sensitivity are comparable to the singular value decomposition-based technique used by the creators of the database [9]. FHR calculated from the RR interval measurements on beat-to-beat basis is crucial for

TABLE I PERFORMANCE OF SWD-BASED FETAL ECG EXTRACTION ALGORITHM ON ABDOMINAL SIGNALS FROM THE ABDOMINAL AND DIRECT FETAL ELECTROCARDIOGRAM PHYSIONET DATABASE

File Name	Identified fetal R peaks					
	Scalp R peaks	TP	FP	FN	Sensitivity (Se)	Positive Predictability (PPV)
R01	644	643	5	1	99.8%	99.2%
R04	632	627	7	5	99.2%	98.9%
R07	627	620	8	7	98.9%	98.7%
R08	651	625	1	26	96.0%	99.8%
R10	637	594	22	43	93.3%	96.4%
Over all datasets					97.4%	98.6%

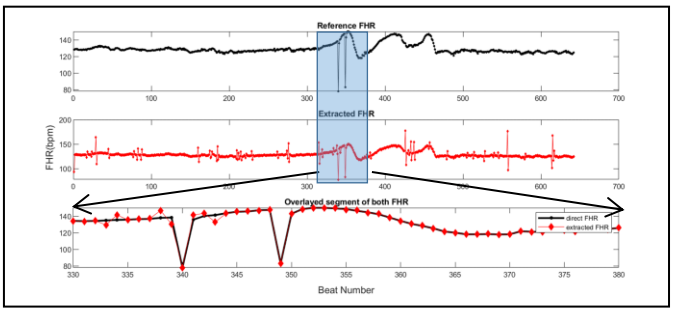

Figure 4 The reference and instantaneous fetal heart rate estimated from extracted fetal ECG, black and red lines respectively of record R01. The last panel shows an expanded segment of 50 beats: from 330 to 380 beats.

clinicians for beat-to-beat FHR variability assessment. The good FHR estimation of this method shown through the Bland-Altman plot supports that SWD based fECG extraction of non-invasive signals is possible for clinical practice. A detailed investigation of SwF parameters tuning is required to determine the most suitable values at different stages of pregnancy and for different quality signals. Furthermore, a wider selection of frequency ranges of separation can be used between 6 Hz and 10 Hz to compare with the 7 Hz used in this study. Further morphological analysis of the extracted fECG is not yet possible, however, the promising results presented here indicate the potentiality of SWD, combined with HOS-based R wave estimator, to reveal the diagnostic information of the fECG for efficient fetal health monitoring in clinical practice through fetal R wave detection.

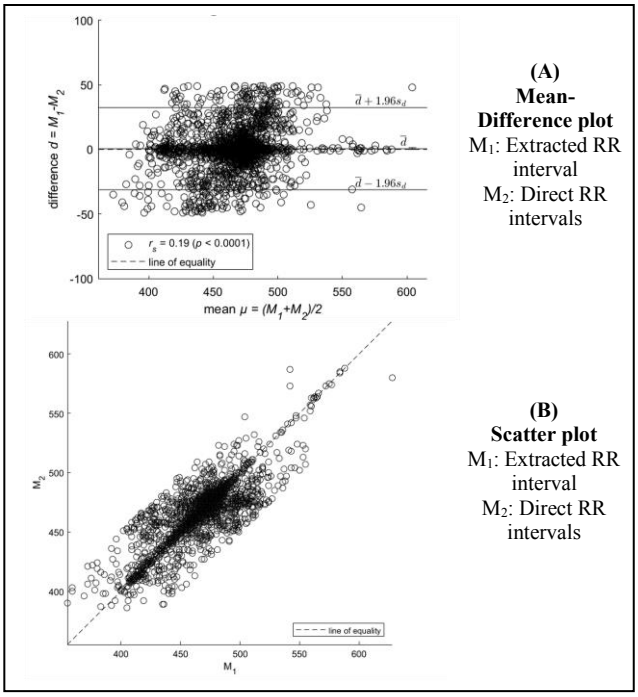

Figure 5 Bland-Altman plot of the RR intervals of extracted and direct fetal ECG of all five recordings. The mean difference is 0.56ms, and the upper and lower limits are 31ms and -32ms respectively

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