Fetal QRS Complex Detection using Semi-Blind Source Separation Framework

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Abstract

Fetal heart rate variability (FHRV) is one of the valuable features of fetal electrocardiography that could be useful to obtain reliable information about the fetal heart activity. In noninvasive systems, the major obstacle for the accurate detection of the fetal QRS (fQRS) complex is the presence of abdominal noise and the maternal ECG (mECG). In this study, we proposed a multistep framework based on semi-blind source separation (SBSS) technique to separate the ECG sources. These sources are ranked automatically to determine the cardiac channel reference and their ECG R-peaks. Using the peaks, the maternal artifacts are reduced from the signals utilizing the quasi-periodicity of cardiac activities. The fetal ECG is also estimated by applying a SBSS stage to the residue of the previous stage. Another channel selection technique, based on a measure of variance, is applied to the channels to rank the channels according to their resemblance with the fetal ECG. The channel most resembling the fQRS is finally used in the peak detection algorithm for finding the fQRS complexes.

The procedure was applied to the CinC challenge 2013 dataset B, which consists of 100 noninvasive signals containing the mECG, fECG, and some abdominal noises. The FHR (Entry 4) and RR interval (Entry 5) time series was calculated respectively with obtained average scores 210.12, and 21.23.

1. Introduction

Fetal electrocardiogram (fECG) signals represent the electrical activity of fetus heart. This signal can be recorded noninvasively from leads mounted on the abdomen of a pregnant woman, especially during the third trimester. The noninvasive extraction of the fECG is believed to be a very helpful tool for the diagnosis of fetal heart well-being, such that the changes in some of its parameters like the PR- and PQ-intervals, the width of the QRS complex, and malformation of P and T waves and the ST segment could be due to the level of fetal oxygenation (Symonds E M) [1]. However, the recorded fECG signal is contaminated by some stronger sources of interference such as the maternal electrocardiogram (mECG), random non-cardiac noises such as uterine EMG and other environmental noises. The fECG is typically obscured by the mECG with 3-15 times, and uterine EMG with 2-10 times stronger amplitudes [13]. Considering such a low signal to noise ratio (SNR), the problem of fECG extraction can be defined in terms of a twofold filtering situation: eliminating the effect of cardiac source of the mother's heart, and rejecting other non-cardiac signals/noises by preserving the fetal cardiac waves, especially the QRS complex. To do so, various methods have been developed since the 1960s and are continued up to now [13]. In the past decade recent approaches have been more concentrated on multi-channel blind source separation (BSS) methods, such as Independent Component Analysis (ICA) [4] [5]. The more effective approaches to fECG extraction consist of a multistage procedure, to reject the interferences one by one, by employing combined denoising and signal/noise separation methods. Herein, a framework is presented based on semi-blind source separation and periodic component analysis (πCA) procedure [6], to extract the fetal cardiac source from non-cardiac signals.

The proposed framework is described in the following sections. The method has been applied on CinC2013 dataset, described in the following section and the results of utilizing the approach is brought in the Section IV. In order to compare the performance of the proposed scheme we applied a state-of-the-art non-blind source method, which has been reported to perform better fECG detection as compared to ICA is used as benchmark [11]. The paper ends with concluding remarks and future perspectives.

2. Database description

The proposed approach has been applied on the abdominal and direct fetal electrocardiogram Databases, which have been recorded for 60sec from the abdomen of 5 pregnant women between 38 and 41 weeks of gestation using four typical spiral electrodes in the Department of Obstetrics at the Medical University of Silesia [7]. The electrodes simultaneously recorded maternal abdomen

and direct electrocardiograms from fetal head. The sampling rate of signals was 1000Hz and contaminated by abdomenal and other environmental noises, plus the cardiac activities of the mother's heart with an amplitute 3-10 times greater than the fECG signals. The database used in CinC2013 fetal QRS detection competition, where divided into train data with 50 files and 100 files as test data.

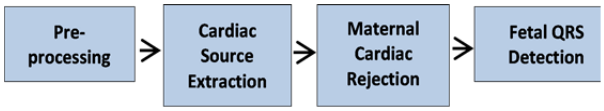

Figure1. The overall data processing diagram to fetal QRS complex extraction.

3. Methodology

A multistep procedure has been employed to reject the unwanted interferences from maternal heart source and abdominal noises and to extract the most components of fetal heart signal to detect its QRS complex. The overall scheme is shown in figure 2. The details of each box are described in the following subsections.

3.1. Preprocessing

The recorded signals contain some non-cardiac interference due to uterine or abdominal electrical activity. The uterine electrical activities (uterine contractions) are infrequent and low amplitude burst electromyogram (EMG) signals, which are mainly characterized by low frequencies, although their frequency content varies from one woman to another, and during the whole pregnancy, some studies have shown that the 0.34-4Hz frequency band contains the main energy of uterine EMG signals [8]. Nevertheless, such activities in comparison with ECG are so strong that besides the fetal QRS, they may even mask some maternal QRS peaks. In order to reject the uterine a bandpass filter composed of the cascade of two second order lowpass filters, with a passband between 10-300Hz has been used. It should be noted that although this frequency band is in appropriate for ECG morphological analysis, it was found to be very efficient for this study, in which we are only interested in the fetal QRS locations.

Figure 2. The overall data processing diagram for Cardiac Source Extraction.

3.2. Cardiac source extraction

After removing the abdominal and uterine electrical activities, one can assume that the major remaining energy is related to the cardiac sources of mother and fetus. However, the electrical activities of mother heart are near 3-15 times greater than the fetal ones and they should be attenuated from the abdominal signals, in order to extract the fetal QRS. The process of extracting such cardiac sources are similar and the detail of this method are shown in Figure 3. As shown in this figure, in the first stage, the cardiac sources have been estimated by a conventional blind-source separation method, known as Joint approximate Diagonalization of Eigenspaces (JADE [10]). Next, a channel ranking method has been used to find the channel with the most similarity with the maternal ECG. This ranking method tries to sort the channels of input signal based on the variance around a given average beat. It is known that a Matched Filter is an optimal filter for detecting a known signal within noise, based on maximizing the signal-to-noise ratio (SNR) of the desired signal. For this, by applying an ECG-like waveform as the matched filter template the SNR of cardiac sources can be enhanced. The template can be obtained from the signal itself.

3.3. Fetal QRS detection

Using the method described in the previous step, the maternal ECG can be extracted and eliminated from the signal subspaces, as indicated in Figure 4. In order to find the fetal cardiac components, a πCA method is employed which is specifically customized for signals such as the ECG, with a quasi-periodic temporal structure [6]. This method is based on the joint diagonalization of the covariance matrix of the data and a lagged covariance matrix found through synchronous averaging of the signals with respect to the maternal ECG R-peaks. The output of πCA is another multichannel signal, with uncorrelated components ranked in descending order of similarity with the ECG of interest. In order to apply πCA for maternal ECG extraction, the time instants of the maternal R-peaks are required. For this, we used the obtained reference ECG channel mentioned in the previous subsection in a peak-detection method that seeks for the maximum points of the data within a sliding window. Using the maternal R-peaks, πCA has been applied to the preprocessed data to sort the components according to their resemblance with the maternal ECG. These components have been rejected or decreased from the signal's subspace using a deflation algorithm [14]. In this method each time the strongest cardiac component is eliminated by nulling their subspace or de-noised by wavelet de-noising method. In this study, a five level Daubechies wavelet was used for this purpose. Next, the

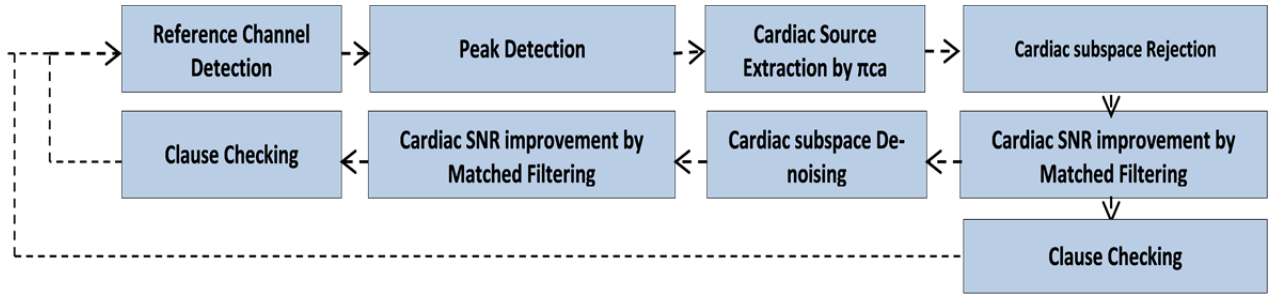

Figure 3. The data processing diagram to fetal ECG extraction.

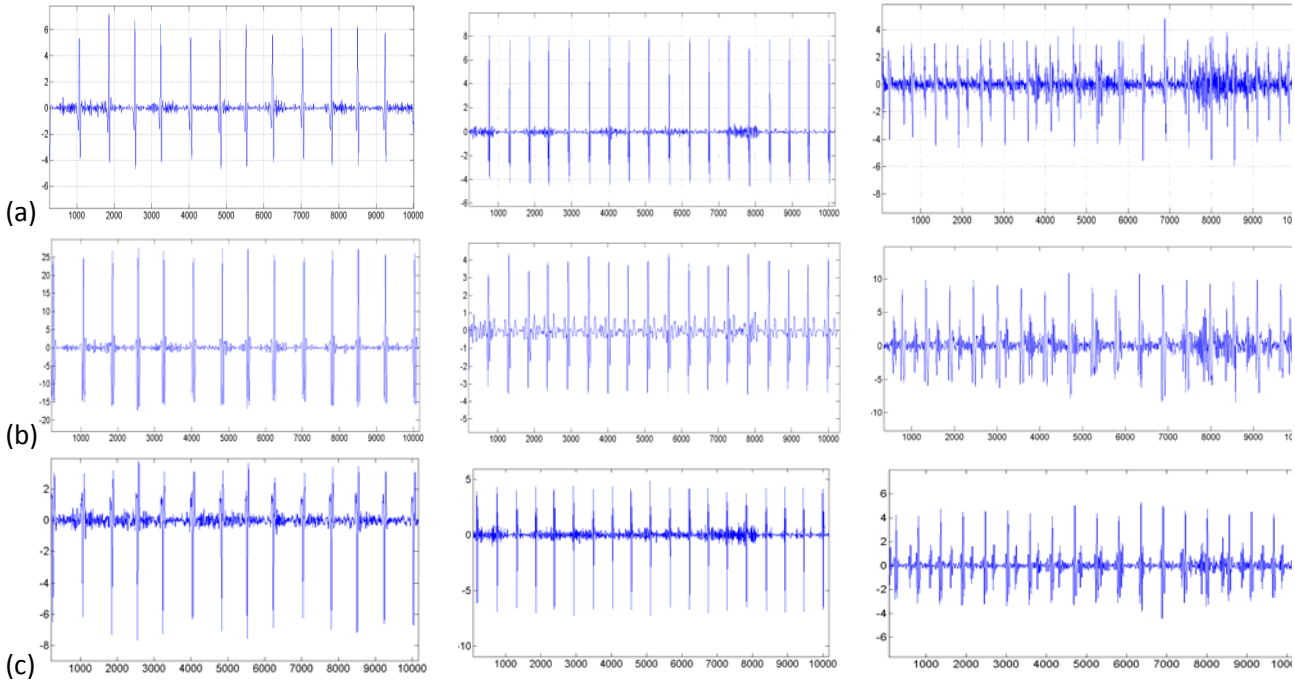

Figure 5. Some typical examples of output of procedure (a) extracted fetal reference (b) above signal after employing matched filter (c) obtained fetal reference to QRS detection.

signal is back projected to the original subspace and the stopping criterion of the loop (based on the amount of signal denoised) is checked. In this study, we used the ratio of average of 5-95 percentiles of values before and after the cardiac elimination process as the stopping criterion. This value was found to be 3.5 (scaleless value). After removing the maternal ECG components from the signal, the cardiac source extraction process as described at previous subsection is applied on the remaining data to detect the most purified fECG component, which can be used to detect the fetal QRS peaks. These peaks as for R-peaks detection process of πCA have been found by a simple peak-detection method that looks for attaining the maximum points of the data within a sliding window.

3.4. Benchmark: sequential non-blind source method

As a benchmark, we employed a sequential analysis method [11], which estimated the fECG signal by step-by-step elimination of non-blind source interfaces from the signal. The first step of this algorithm is to remove the baseline wander and power-line interferences. Next, the maternal QRS peaks are detected using a peak detection procedure. These peaks are utilized in a mECG cancellation step, which is based on the averaging and scaling method proposed in [12]. After removing the mECG from the signal, a peak detector algorithm is

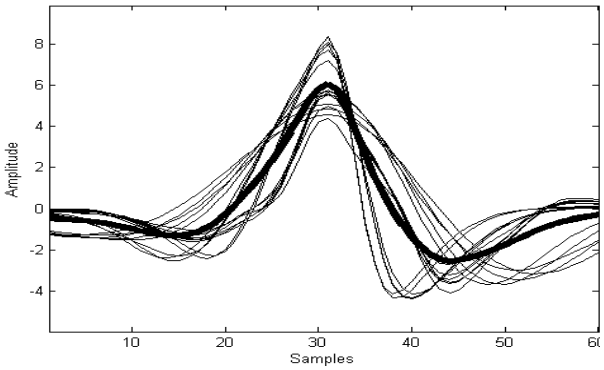

Figure 4. The signal-extracted matched filter.

applied to the remaining signal to find fetal QRS complex.

4. Experimental results

The overall scheme to extract the fetal QRS complex has been summarized in Fig. 3. This approach is applied on the CinC2013 direct fetal ECG database. The proposed method described in the previous section was applied to this data. The average values of 10 heart beats with a window length of 60 samples around the R-peak has been used as the matched filter template. The butterfly plot of typical templates are shown in Figure 4. These temples were used in the matched filter to improve the cardiac components SNR, in order to detect the R-peaks of the ECG signal more precisely. As mentioned in the previous section, after rejecting the abdominal and uterine electrical activity form the signal, the strongest source of interference is associated to the maternal heart. As indicated in the cardiac source extraction stage in Figure 3, such sources have been found by means of R-peaks of the signal after applying the JADE algorithm to find the source of signal followed by the sorting procedure. We used the first output of this algorithm as the reference channel. The plot of typical examples of such channels are presented in figure 5(a). Figure 5(b) showed those selected channel after employing mentioned matched filter to improve the SNR of fetal ECG. The resulting fetal ECG and its QRS are shown in Figure 5(c). Using this procedure and by utilizing the conference scoring tool, we obtained the overall score of 210.12 on the 50 files of train data for FHR and 21.23 for RR. In comparison with that framework, the performance of employing the mentioned sequential non-blind source method, that described above, on the training files was 1810 for FHR and 69.65 for RR.

5. Discussion

A semi-blind source framework with multi step approach was proposed to extract the fetal QRS complex, using a matched filter with a signal-extracted template, finding the source of cardiac activity by a JADE algorithm, and rejecting the cardiac components from the signal subspace by nulling their subspace or wavelet de-noising them. We compared the output of our procedure with a sequential non-blind source method and the results shows that our framework outperforms that method. The most important problem for the fetal ECG is low SNR and the overlap between its subspace with maternal ECG. In this study we used πCA method to extract the maternal cardiac components, rejecting these components step-by-step, by checking a threshold to preserve the fetal components. In addition, in the channel ranking step, by specifying the maternal beat rate and the fetal beat rate and finding the most appropriate reference channel, we provided the best matched filter template, each time to improve the corresponding signal's SNR. In future work, we can focus on the optimization of the developed method and extending it to a fully automated method applicable to real-time recorded signals.

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