A Multi-step Approach for Non-invasive Fetal ECG Analysis

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Abstract

Non-invasive monitoring of fetal cardiac activity is of great clinical interest to assess fetal health. To date, however, difficulties in detecting fetal beats from abdominal mother recordings prevented the possibility of obtaining reliable results. In this study a multi-step approach for the analysis of non-invasive fetal ECG is proposed. The first steps concern the pre-processing stages of baseline removal and power line interference canceling. The successive operations are: Independent Component Analysis (ICA) for maternal ECG extraction; mother QRS detection; maternal ECG canceling using a PQRST approximation obtained by weighted Singular Value Decomposition (SVD); second ICA applied to enhance the fetal ECG signal; fetal QRS detection. The results obtained in Physionet Challenge 2013 on the test sets are expressed as two scores (HRmse and RRrmse) measuring respectively the matching between the reference annotations of fetal HR and RR time series and those estimated with the developed software. The results obtained on the learning set are: sensitivity=99.4%, positive predictive accuracy=99.2% and HRmse=1.52 bpm^2, RRrmse=2.11 ms. The scores for the open test set are: HRmse=34.0 bpm^2, RRrmse=5.10 ms. The scores for the hidden test (open source section) are: HRmse=187 bpm^2, RRrmse=21.0 ms.

1. Introduction

Despite significant advances in electrocardiography and signal processing techniques, the analysis of fetal electrocardiogram (fECG) still needs a great deal of improvements to become a valid alternative to the commonly used Doppler ultrasound monitoring technique. The reason for this limitation is that the fECG is affected by low signal-to-noise ratio, small amplitude, baseline drifts, power line, electromyogram (EMG), mother respiration, motion artifacts and electrode contact failure. Therefore, although fetal QRS detection could be simple in optimal conditions, it is very challenging to obtain reliable results in real clinical practice. According to the review of Sameni [1] main methods for fECG extraction include linear or non-linear decomposition and adaptive filtering. Blind or semiblind source separation, categorized as linear decomposition approaches, were typically used for extracting and denoising fECG signals [2]. Non-linear techniques were also applied such in the work proposed by Kotas [3]. Adaptive filtering is another common approach for maternal ECG (mECG) canceling and fECG extraction [4], even if Zarzoso et al. [5] demonstrated that blind source separation (BSS) approach outperforms adaptive filtering. However maternal ECG canceling [6] is the most applied method and Martens [7] showed its robustness respect to the BSS approach. In this context the first part of Physionet Challenge 2013 [8] addresses the development of an algorithm for accurate detection of fetal QRS from non-invasive abdominal signals. In this paper we propose a multi-step approach for fetal QRS detection described as follows: 1) impulsive artifacts, baseline wandering and power line interference removal; 2) source separation, selection and canceling of maternal ECG; 3) source separation; 4) detection of mother QRS and canceling of maternal ECG; 5) source separation of residual signals; 6) detection of fetal QRS complexes and selection of the best estimated annotations of fECG. The developed code was submitted for the Physionet Open-Source Challenge call

2. Methods

The dataset of the Challenge consisted of three sets: a learning set of 75 records provided with reference annotations of fetal QRS; an open test set of 100 records whose annotations were not provided and reserved for evaluation of challenge entries; an hidden test set whose records were not published and reserved for evaluation of open-source Challenge entries. Each recording included 4 channels of mother abdominal ECG sampled at 1KHz and collected for 60s. Signals were affected by noise, artifacts, EMG, power line interference and baseline wandering. Our proposed algorithm, consists of the following steps.

- *Impulsive artifacts canceling*. For each ECG channel a median filtering with a 60ms window was applied and the absolute difference between the original and the median filtered signal was obtained. If the absolute difference was over an estimated threshold, the corrupted interval was replaced with an estimated value.

- *Baseline wandering removal*. The baseline signal was computed applying a low pass first order Butterworth filter in forward and backward direction to avoid phase distortion (cut off frequency at 3.17Hz). Each detrended signal was obtained as the difference between the original signal and the estimated baseline. In presence of residual artifacts due to fast baseline movements, median filtering (0.26s window) was applied. This last method even if more efficient than the linear filtering, generates a non-linear phase distortion, which could impair the next steps of sources separation.

- *Power line interference canceling*. The existence of power line interference was assessed and its frequency identified by using the power spectral density estimation according to the modified averaged periodogram. If power line interference was detected, a notch filter (forward-backward, zero phase, 1Hz bandwidth) was applied to remove its characteristic frequency and its next three harmonics. Figure 1 shows the four channels of record "a03" of Physionet database after these two pre-processing steps.

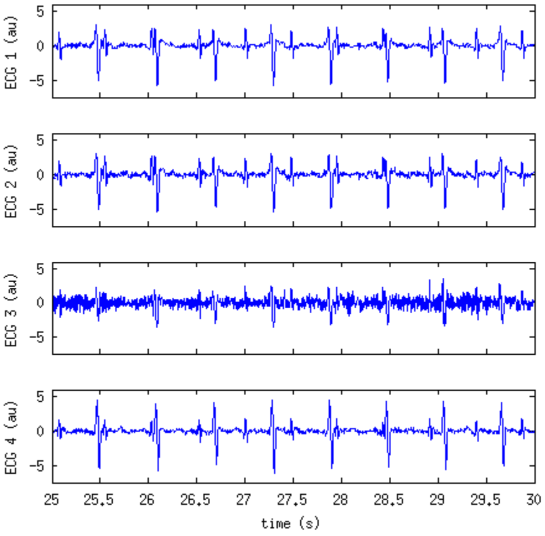

Figure 1. Abdominal maternal ECGs of record "a03", after cleaning, baseline and power line removal.

- *Separation and enhancement of maternal ECG*. Once the pre-processing steps were performed, the Independent Component Analysis (ICA) was applied to separate the maternal ECG from the other components. The ICA requires the following assumptions: statistically independent sources, non-gaussian (at most one may be gaussian) and/or autocorrelated sources, instantaneous linear invariant mixing matrix and number of measured signals equal or greater than the number of sources. In our case these two last assumptions are not fully satisfied because EMG, residual noise and artifacts increase the number of sources and fetal movement leads to not invariant mixing matrix. In addiction ECG sources, being waves of depolarization and repolarization, are moving in the space spreading through the heart. This leads to an increase of the number of sources and to a time variant mixing matrix. However the mother cardiac muscle is quite far from the abdominal lead and the maternal ECG is the strongest and pervasive independent source of the four measured abdominal signals. For this reason it will result in at least one independent component. Moreover ICA will be able to separate also the fECG but in case of clean signal and invariant mixing matrix only. In order to obtain the best separation of maternal and fetal ECG both algorithms based on sources autocorrelation (Second Order Blind Identification, SOBI) [9] and on sources non-gaussianity (Joint Approximate Diagonalization, JADE [10], FastICA [11]) were tested. The most reliable results were obtained applying the FastICA of Hyvarinen with deflationary orthogonalization. The hyperbolic cosine was selected as preferred contrast function as it produces more robust estimates. In case of failure of convergence, the kurtosis instead of hyperbolic cosine was used. Figure 2 shows the results of ICA applied to the pre-processed record "a03" (see Figure 1). In this example the maternal ECG alone is present in the ic2 component while the third component contains mixed maternal and fetal ECGs (ic 3).

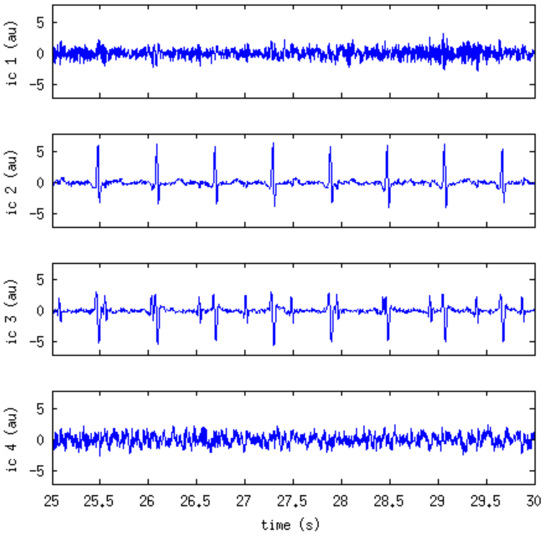

Figure 2. Components resulting from ICA application to the signals of Figure 1.

- *Mother QRS detection*. To get a precise time location of mother QRS and therefore to allow an accurate canceling of the maternal ECG, all the four signals extracted from the previous step were interpolated at 4KHz with Fourier transform method. The best maternal ECG channel was identified taking into account a priori knowledge on its pseudo-periodicity. A derivative filter was applied to the identified maternal ECG channel implementing a moving average of 9ms on the output of the comb-filter x(n)-x(n-k) where the delay "k" is 16ms. The absolute value of the raw derivative signal was filtered by a forward-backward Butterworth bandpass filter (6.3-16Hz). The QRS was detected with an adaptive threshold on derivative amplitude automatically initialized and recursively updated at each new detection. Moreover the value of the threshold was changed with the temporal distance from the previous QRS detection. The fiducial point of each detected QRS was identified with the maximum of derivative signal whose sign was determined during the initialization phase (see details of "QRSdetectorM.m" function).

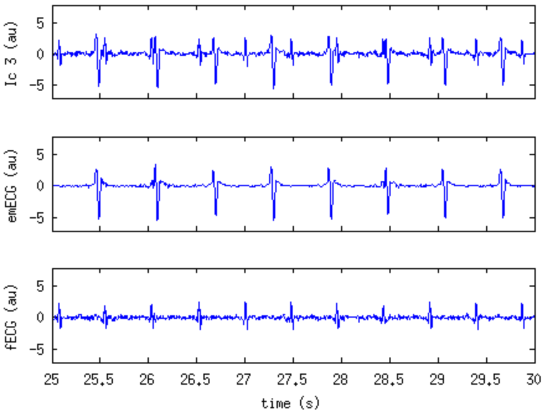

Figure 3. Top-down: 3th component resulting from the previous application of ICA; estimated maternal ECG obtained by SVD; Fetal ECG obtained through estimated maternal ECG canceling.

- *Maternal ECG canceling*. This procedure was applied at each channel using the Singular Value Decomposition (SVD) to approximate each beat of maternal ECG. A trapezoidal window (whose length depended on the mean RR-interval on the whole record) was used to select and weight the signal around each detected mother QRS. A matrix was built using these weighted PQRST segments as columns and it was decomposed by SVD. Only the first three singular values were used to rebuild a matrix of approximated PQRST. This choice, in most of records, provided a good estimation of the mother beats without including fetal QRS features. The approximated PQRST segments were then connected with a straight line obtaining a signal that was subtracted from the original one to cancel the maternal ECG component. Figure 3 shows the signal obtained after the application of maternal ECG canceling to the 3th independent component of Figure 2.

- *Separation and enhancement of fetal ECG*. In this step ICA was applied to the residual signals in order to separate/enhance the fECG from the other components. The method was the same used for maternal ECG separation.

- *Fetal QRS detection*. It was performed applying on all the four ECG channels a derivative filter consisting in a moving average of 5ms of the output of a comb-filter with a delay k of 8ms. Once ECG signal was filtered, a 1st QRS detector was applied using an algorithm similar to that used for maternal ECG but with different parameters (a priori mean RR-interval, threshold, QT-mask; see details on submitted code). Thus, from the detected fetal QRS the RR time series were extracted and the longest segment whose values are close to the mode of RR series was identified. The corresponding ECG interval was considered to have a good S/N ratio and it was used for the initialization of a 2nd QRS detector algorithm which was applied in forward/backward direction, respectively from the beginning/end of the interval to find the maximum of a weighted derivative signal (with a priori defined sign). The weights were defined by a trapezoidal window enhancing the samples close to a predicted QRS position which was obtained by estimating an autoregressive (AR) model for the RR time series. The AR model was implemented by an adaptive filter in predictive form. The filter coefficients were computed on the initial interval and updated beat to beat by the Least Mean Square (LMS) algorithm. The AR model provided a predicted RR duration time i.e. the expected position of the next fetal QRS (see details of "QRSdetectorF2.m" function). The fetal QRS detection procedure was applied to all the four signals obtaining four hypothetical QRS annotations and the relative RR series. Finally the estimated fetal QRS annotations were selected applying a criterion based on a priori knowledge of typical fetal RR values and minimizing: the mean of absolute RR first derivative, the mean of absolute of RR second derivative and the number of detected fetal QRSs matching mother QRSs.

Our software was tuned on the learning set comparing the estimated and the reference annotations .and was tested in a full automatic unsupervised mode using the same parametrization for all records of the learning set and the test set. A subset of 69 records was selected from the learning set excluding partially/badly annotated records (a33, a38, a52, a54, a71, a74).

3. Results

The evaluation of the results was obtained using both classical sensitivity (SE) and positive predictive accuracy (PPA) and two indexes obtained by the mean square of differences method as proposed by Physionet Challenge

[8]. Regarding SE and PPA calculation, the QRS detected was considered as a true positive if it was within a temporal window fixed to 140ms. The indexes proposed by Physionet Challenge were "HRmse" and "RRrmse" The first measures the difference between the fetal average HR time series obtained from the estimated annotations and that obtained from the reference while the second matches the estimated fetal RR interval time series with the reference. The performance on the 69 records subset of the learning set was Sens=99.4%, PPA=99.2% and HRmse=1.52 bpm^2, RRrmse=2.11 ms. The evaluation on the open test set was obtained uploading the estimated annotations for all the 100 records on the Physionet Challenge website [8]. The average scores obtained on the open test set with our last entry are HRmse=34.0 bpm^2, RRrmse=5.10 ms. The scores for the hidden test (open source section) are HRmse=187 bpm^2, RRrmse=21 ms.

4. Discussion and conclusions

The proposed method integrated two of the most used approaches for fECG extraction from mother abdominal ECGs: source separation and maternal ECG canceling. Although ICA would be the method of excellence, the departures from its assumptions often lead to failure in fECG separation. On the other hand maternal PQRST canceling requires a compromise between the need to track mother QRS changes in order to have a good canceling and the need to preserve fetal QRSs, especially in case of overlapping. Moreover, after maternal ECG canceling, fECG can be still affected by noise and artifacts. About ICA sources separation, one of the main requirements is that the number of sources is not greater than the number of measured signals. The proposed multi-step approach was designed to reduce the number of sources as much as possible (baseline wandering, power line interference, maternal ECG) in order to improve the chances of ICA to isolate fECG. The developed multi-step algorithm produced overall good results but it performed badly on some critical records where the fECG signal was very low compared to noise and/or to EMG components. To solve this issue, different ICA algorithms (FastICA, JADE, SOBI) with their variants were tested without achieve an improvement of performance respect to the basic implementation of FastICA. The measurement/EMG noise seems to have the most negative effect on fECG extraction process impairing ICA. The attempts to enhance fECG respect to noise and EMG by filtering did not improve ICA results in fECG separation. In conclusion, the results obtained with our system shows that non-invasive fECG analysis can be feasible if protocol for abdominal ECG acquisition include: i) accurate skin-electrode contact in order to reduce the electrical noise and artifacts ii) care to reduction of muscular contractions.

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