Multi Stage Principal Component Analysis Based Method for Detection of Fetal Heart Beats in Abdominal ECGs

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Abstract

Electrical activity of fetal heart is present in registered abdominal signals, however in real clinical recordings energy of this signal is so small that classical multivariate analysis based methods (e.g. Independent Component Analysis) fail to extract it for further analysis. Principal Component Analysis based method was used for truncated representation and subtraction of cardiocycles of maternal ECG. The energy of fetal ECG component then remains sufficient when compared to other components of the remaining signal to be concentrated in the first component obtained during the second stage Principal Component Analysis. This stage was performed not for extracted cardiocycles, but for the whole leads of the signal. The procedure extracts maximal amplitude of the sought signal regardless to the orientation of the fetus in multilead recording cases. Two stage detection of fetal heart beats is performed in band-pass filtered first principal component. Maximization of correlation with sliding QRS model gives the final time point of fetal heart beat in the region preliminary detected by means of simple amplitude thresholding. Third stage Principal Component Analysis was used to reconstruct the cardiocycles of fetal ECG for further analysis. The algorithm was tested with PhysioNet Challenge 2013 signals. Preliminary results of the detection of fetal heartbeats by our method for the PhysioNet Challenge 2013 on set B were: Average Score (event 1/4): 1391.70; Average Score (event 2/5): 45.49.

1. Introduction

More then 100 years passed after first demonstration of registered fetal electrocardiogram (FECG) by Cremer, but the method did not became a routine method in everyday practices. Although information carried by this signal is of crucial importance, technical difficulties in registration and evaluation of it made extracted information diagnostically controversial. Fetal heart activity monitoring in many cases can provide the only diagnostic information obtained in non invasive way about risks of fetal hypoxia, acidemia or even asphyxia. Usually it is done using ultrasound Doppler signal analysis based devices registering fetal heart rate (FHR) and results are evaluated according recommendations (e.g. [1]). Difficulties in usage of the devices usually cause false-positive results. FHR patterns from poor quality recordings rarely signify fetal hypoxia or ischemia and use of this technology leads to more operative vaginal and cesarean deliveries [1]. Also there is no evidence that the use of such continuous intrapartum fetal monitoring improves newborn outcomes [2]. Promising results show combined devices using Doppler ultrasound devices and fetal ECG registered by means of scalp electrode. Such devices monitor not only FHR but also a proxy for the ST segment of the fetal QRST complex – the quantitative ratio between the amplitude of the fetal T and R waves – and the presence or absence of a biphasic ST segment [3]. Such technique is invasive and limited to usage only during labor and only in certain fetus positions. Electrical signals recorded from the maternal abdominal wall contain FECG as one component, but the energy of it is small while compared firstly to maternal electrocardiogram (MECG) component and various other signals. Most successful results in separation of the components of these signals achieved using multivariate analysis: singular value decomposition [4] and independent component analysis (ICA) [5]. However the optimistic conclusions presented in last mentioned publication were derived on the basis of a simulation experiment which was not representative to real-life problems.

Our idea was to apply multistage multivariate analysis for separation of components of abdominal electrical signals in aim to detect fetal heart beats and reconstruct their shape for further analysis.

2. Methods

The method starts with MECG cancellation, the idea of which is similar to described in [6]: Construction of the MECG beat template and subtraction of this template from the analyzed signal in the places where individual

beats occur. Instead of beat template we used MECG beats reconstructed by means of principal component analysis (PCA) based truncated expansion. We used the similar procedure as described in our previous works [7]. Due to comparatively high amplitude of MECG, the fiducial points of cardiocycles were easily detected by combined method using amplitude thresholding and maximization of correlation with sliding QRS template (see [7] for details). PCA was performed on two dimensional array, every column of which is formed of extracted and concatenated excerpts of MECG representing one particular cardiocycle in all registered leads. So, one column of X redundantly, but comprehensively represents one cardiocycle:

$$\mathbf{X} = \begin{matrix} x_{1,1} & x_{1,2} & \dots & x_{1,n} \\ x_{2,1} & x_{2,1} & \dots & x_{2,n} \\ \dots & \dots & x_{i,j} & \dots \\ x_{p,1} & x_{p,2} & \dots & x_{p,n} \end{matrix}, \quad (1)$$

here $x_{i,j}$ is the i[th] sample of the j[th] cardiocycle. The excerpt length of 600 samples surrounding fiducial point of cardiocycle (peak of R-wave) at 200[th] position in it, was defined during preliminary tests. Every vector $\boldsymbol{x}_i$ representing ordinary MECG cardiocycle is then represented by linear combination of the basis functions ϕ_k multiplied by coefficients $w_{i,k}$:

$$\mathbf{x}_i = \sum_{k=1}^{p} w_{i,k} \varphi_k \ . \quad (2)$$

As basis functions we used eigenvectors of covariation matrix of two dimensional arrays X containing samples of cardiocycles:

$$\mathbf{R}_x = \mathrm{E}\left[\mathbf{X} \cdot \mathbf{X}^T\right]. \quad (3)$$

First three basis functions, according to our preliminary tests representing more then 90% of signal variance were used to reconstruct MECG cardiocycles which we subtracted from leads of abdominal signals where they occurred.

Instead of independent component analysis used by many authors for final separation of MECG, FECG and the rest of the signal components we selected PCA. Our selection is based on the idea that after MECG cardiocycles subtraction from the abdominal wall signal, FECG will be the signal component having highest variance and PCA will construct first principal component representing especially it. Moreover in multilead registration case it will automatically maximize amplitude regardless to the position of fetus.

Covariation matrix in this case is calculated from two dimensional arrays of data, columns of which contain samples of whole signal leads after subtraction of MECG cardiocycles. Eigenvectors of this covariation matrix are used to construct matrix of principal components:

$$Y = \Psi^t X \ . \quad (4)$$

Fiducial points of FECG cardiocycles are found in the same way as ones of MECG, but using only this newly calculated first principal component.

Third stage PCA was used to reconstruct FECG cardiocycles. It was performed in the same way as reconstructing MECG cardiocycles, but using fiducial points of FECG and shorter intervals of 450 samples surrounding them. Fiducial point was in 150[th] position of this interval. Minimal yet sufficient number of basis functions – four – for reconstruction of FECG cardiocycles was selected according to our experience described in detail in [7] using Wold's cross-validatory estimation criteria [8]:

$$PRESS(m) = \sum_{i=1}^{n} \sum_{j=1}^{p} \left({}_m\hat{x}_{ij} - x_{ij} \right)^2 , \quad (5)$$

where ${}_m\hat{x}_{ij}$ is the estimate of the original data set based not on all but the first m basis functions, x_{ij} - the original data set.

Investigations were performed on PhysioNet Challenge 2013 datasets containing 4 lead abdominal wall recordings registered using 12 bit resolution at 1000 Hz sampling rate.

3. Results

Example of signals before and after MECG cardiocycles cancellation is shown on fig.1.

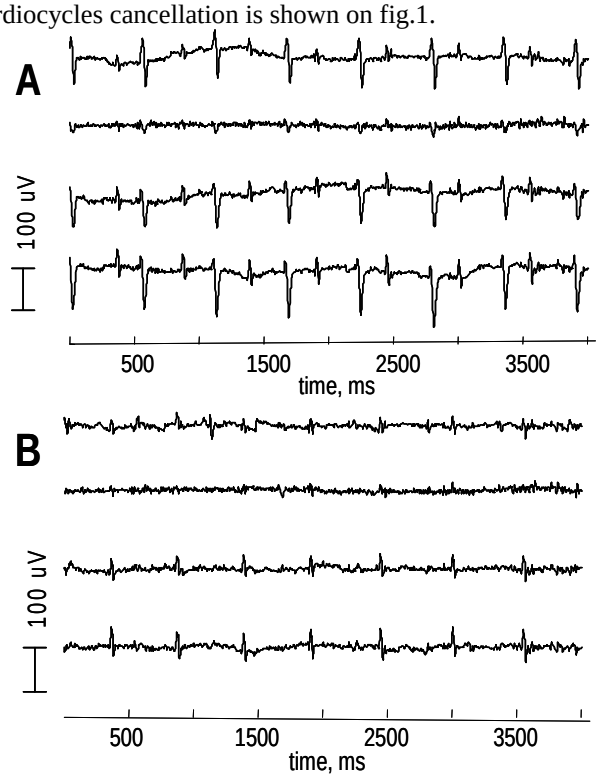

Fig.1. Original abdominal ECG recording (A) and the same recording after MECG cancellation.

As one can see subtraction of MECG cardiocycles did not left any significant destruction in the signals or contamination of FECG signal.

Example of four principal components calculated from abdominal ECG signals after subtraction of MECG cardiocycles shown on fig.2.

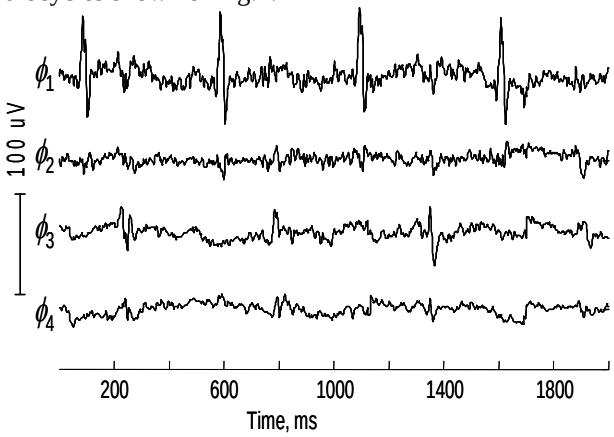

Fig.2. Four principal components calculated from abdominal wall signals after subtraction of MECG cardiocycles.

FECG with dominating amplitude is present on first principal component, which was used for further detection of fetal heart beats. Third and fourth principal components contain some remains of MECG and other components of the abdominal wall signal.

Example of detected FECG heartbeats in raw abdominal wall signal together with reference points given in set A of PhysioNet Challenge 2013 data is shown on fig.3.

Preliminary results of the detection of fetal heartbeats by our method for the PhysioNet Challenge 2013 on set B were:

Average Score (event 1/4): 1391.70

Average Score (event 2/5): 45.49

As one can see from the traces in fig.3, the method is able to detect fetal heartbeats even overlapping with maternal ones. Having no reference FECG we are not able to evaluate shape distortions of such cases, but visually we expect them to be negligible.

Example results of third stage PCA based reconstruction of FECG cardiocycles is presented in fig.4.

This procedure does not reconstructs the whole continuous signal, but only the cardiocycles – excerpts of the signals around the fiducial point of the cardiocycle. Visual evaluation of the quality of reconstructed signals suggests possibility to evaluate duration of Q-T interval or S-T segment elevation in particular lead.

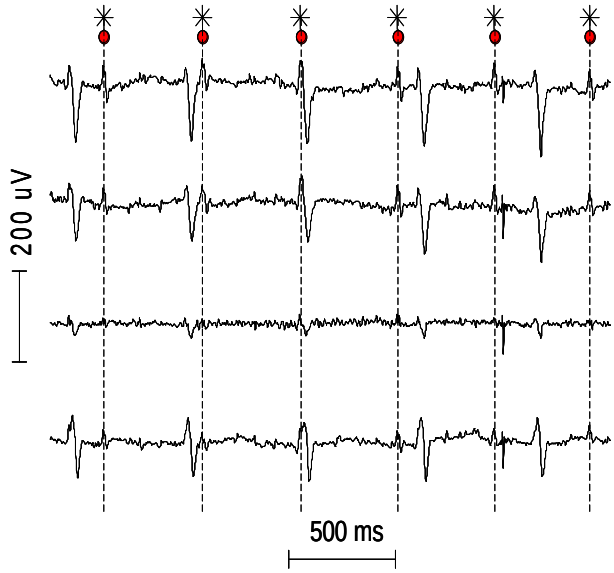

Fig.3. Four leads of abdominal wall signal with marked fetal heartbeats. Stars show results of our method, filled circles show reference time points given in set A of PhysioNet data.

4. Discussion

Our results confirm suggestions made by M.Kotas in [9], that classical examples of usage of multivariate analysis methods, such as Independent Component Analysis for MECG and FECG separation fail in majority of real clinical cases due to big differences in energy levels of MECG and FECG. Other interfering signals also play an important role pushing sought FECG signal into last place or simply discarding it during ICA procedure. Therefore procedure of suppression of MECG is of great importance and final result depends on quality of it.

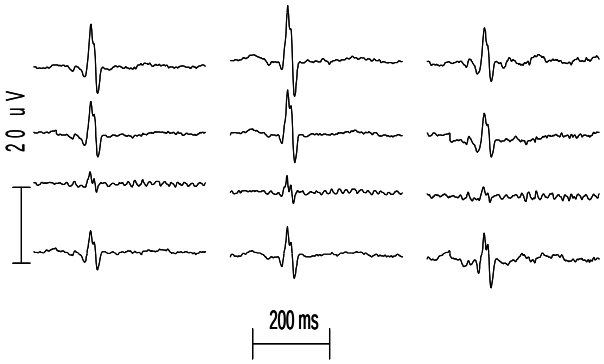

Fig.4. Three consequent cardiocycles in 4 original leads reconstructed by means of third stage PCA procedure.

Applied cardiocycle–vise PCA reconstruction in some cases succeeded to cancel MECG cardiocycles even overlapping with FECG cardiocycles without significant harm to the shape of the last one. It allowed detection of

fetal heartbeats even covered by maternal ones in original signal.

We tested both PCA and ICA methods for separation of FECG from signals after subtraction of MECG cardiocycles. ICA gave about the same level of FECG amplitude measured by QRS peak. However ICA is giving unsorted independent components, therefore every time it is necessary to detect which component is representing sought FECG signal. PCA always gives calculated principal components sorted in descending order according their energy represented by variance. The problem could occur in cases when FECG will have not the highest energy after subtraction of MECG cardiocycles. However we did not found such cases in our analyzed signals.

Final detection of time points of FECG heart bytes was performed on one lead, which concentrated all energy of FECG. PCA guarantees that this component always will have maximal amplitude regardless to the position of fetus. So all further measurements (e.g. QT interval length) could be performed on it. However evaluation of ST elevation requires more comprehensive representation in more then one projection. Therefore we used cardiocycle–vise PCA reconstruction of FECG from original leads. The quality of reconstructed FECG cardiocycles could be evaluated using parallel recordings from scalp electrode. But it we leave for future investigations.

4. Conclusion

Elaborated multistage principal component analysis based method for detection of fetal heart bytes in abdominal wall signals is able to detect time points for evaluation of fetal heart rate and using them reconstruct fetal cardiocycles for further shape evaluation.

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