independent component analysis,
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SEPARATION OF ABDOMINAL FETAL ELECTROCARDIOGRAMS IN TWIN PREGNANCY

A combined application of independent component analysis and projective filtering of the time-aligned ECG beats is proposed to solve the problem of fetal ECG extraction from multi-channel maternal abdominal electric signals. The developed method is employed to process the four-channel abdominal signals recorded during twin pregnancy. The signals are complicated mixtures of the maternal ECG, the ECGs of the fetal twins and noise of other origin. The independent component analysis cannot separate the respective signals, but the proposed combination of the methods allows to suppress the maternal ECG and when the level of noise is low it leads to an effective separation of the twins' signals.

1. INTRODUCTION

The fetal electrocardiogram (FECG) is a source of the complex diagnostic information that can be analyzed by obstetricians for the assessment of the fetal well-being. Numerous attempts have been made to develop effective methods of the FECG signals recording and analysis. In this paper we focus on the noninvasive methods. They are based on the signals recorded from the maternal abdominal wall. However, such signals contain not only the fetal ECG but primarily the maternal electrocardiogram and various types of contaminations (e.g. mother's muscles activity or artifacts resulting from fetal movements). An essential problem is the efficient suppression of the maternal electrocardiogram (since its amplitude many times exceeds the level of the FECG). The simplest method of the interfering maternal QRS complexes removal is blanking [11]. In this method, with every maternal QRS complex detected, the corresponding segment of the abdominal signal is replaced by the isoline values. However, in any case of coincidence of maternal and fetal QRS complexes, the blanking approach leads to some information loss in the FECG signal. For the signal parameters close to typical values, the number of lost fetal QRS complexes fluctuated around 12 % [11]. This can be coped with in the longitudinal ambulatory fetal monitoring where the fetal heart rate (FHR) trace is averaged over 2.5 s periods (which is needed for classical signal analysis: baseline estimation and acceleration/deceleration pattern recognition). Unfortunately, the signal loss resulting from blanking makes the assessment of beat-to-beat variability of FHR rather impossible [6].

Therefore more advanced methods of maternal ECG suppression were developed. Two most important approaches to cope the problem can be distinguished. The first one is based on the analysis of single-channel signals. It involves the approximate repeatability of the ECG beats to achieve the goal of the abdominal signals separation. The second approach is based on the analysis of multi-channel signals. A set of important techniques was based on the application of singular value decomposition to the separation of the maternal and the fetal source signals [2]. Application of independent component analysis (ICA), exploiting not only the second (as in [2]) but also higher order statistical conditions of independence, allowed to achieve a great progress in the accomplishment of the separation task [5]. Both mentioned methods involve the redundancy of the multi-channel ECG recordings. Therefore, they require at least three or four signal channels to achieve the goal of the fetal ECG extraction. In cases of twin pregnancy, however, even higher number of channels does not guarantee the methods' success in separating the ECG signals of the twins.

In this work we propose a different solution of the problem. A combination of approaches typical for the multi-channel and the single-channel techniques makes possible exploiting both types of ECG signals redundancy. The independent component analysis performs the spatial separation of the abdominal signals; a single-channel approach based on projective filtering of the time-aligned ECG beats [9] is employed to improve the results of the separation.

2. METHODS

2.1. PROJECTIVE FILTERING OF TIME-ALIGNED ECG BEATS

The main ideas behind the projective filtering can be summarized as follows:

1. Reconstruction of the state-space representation of the observed noisy signal is achieved by application of the Takens embedding operation. A point in the constructed space is a vector:

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$$\mathbf{x}^{(n)} = \left[x(n), x(n+1), ..., x(n+m-1)\right]^T \quad (1)$$

where $x(n)$ is the processed one-dimensional signal, m is the embedding dimension.

2. The learning phase of the method (performed after initial steps, such as QRS complexes detection and ECG beats synchronization) consists in application of the principal component analysis to the construction of local signal subspaces for the vectors (embedding space points) that have the same position within the respective ECG beats (for each position within a beat).
3. The processing phase is defined by projecting individual trajectory points into the corresponding signal subspaces. Later these points will be converted back into the one-dimensional signal.

The detailed description of the method can be found in [9]. The projective filtering allows to suppress the electrocardiographic noise whose spectrum overlaps the spectrum of the desired ECG [10]; the application of this method to fetal ECG extraction from single-channel maternal abdominal signals is described in [8].

An important parameter is the dimension q of the constructed signal subspaces. Its proper choice allows to balance between the method ability to reconstruct precisely the desired component and its ability to suppress noise. With higher values of q the projective filtering is more flexible and can reconstruct the desired ECG with higher accuracy, but the suppression of the undesired components is less effective.

2.2. BLIND SOURCE SEPARATION AND PROJECTIVE FILTERING FOR FETAL ECG EXTRACTION

The blind source separation model, applied to multi-channel maternal abdominal ECG signals, utilizes an observation that the signals from different leads are different linear combinations of the same source signals, independent from one another, generated mostly by the maternal heart and other organs, as well as by the fetal heart. In matrix notation

$$\mathbf{y}^{(n)} = \mathbf{A} \cdot \mathbf{s}^{(n)} + \mathbf{d}^{(n)} \quad (2)$$

where $\mathbf{y}^{(n)}=[y_1(n),y_2(n),...,y_K(n)]^T$ is the measured signals vector, $\mathbf{s}^{(n)}=[s_1(n), s_2(n), ..., s_K(n)]^T$- the source signals vector, $\mathbf{d}^{(n)}=[d_1(n),d_2(n),...,d_K(n)]^T$ - the vector of independent noise.

A is the transforming (mixing) matrix, containing the weights $a_{i,k}$ by which the kth source signal is multiplied before adding to the ith channel, according to the equation

$$y_i(n) = \sum_{k=1}^{K} a_{i,k} \cdot s_k(n) + d_i(n) \quad (3)$$

which is equivalent to (2).

Knowing the mixing matrix A, the source vector could be estimated simply by inverting this matrix and the following operation

$$\hat{\mathbf{s}}^{(n)} = \mathbf{A}^{-1}\mathbf{y}^{(n)} = \mathbf{A}^{-1}\mathbf{A} \cdot \mathbf{s}^{(n)} + \mathbf{A}^{-1}\mathbf{d}^{(n)} = \mathbf{s}^{(n)} + \mathbf{d}'^{(n)} \quad (4)$$

where $\mathbf{A}^{-1}$ is the separating matrix.

Since **A** is unknown in advance, calculation of the separating matrix should be performed in other way, e.g. by exploiting the conditions of the statistical signals independence. In this study we applied the method of independent component analysis which performs the separating matrix estimation by Joint Approximate Diagonalization of the cumulant Eigenmatrices (JADE [4]).

Although the source signals estimation is based on the statistical conditions of independence, the common origin of some estimates does not justify their independence. In modern approaches [3] source subspaces rather than source signals separation is considered. The source signals estimates are grouped according to their origin (the maternal heart, the fetal heart, etc.) and compose the subspaces which can be used to reconstruct the components of interest of the measured signals. If the set containing the numbers of the source signals that belong to the chosen source subspace is denoted by Φ , the operation can be defined as

$$y_{\Phi,i}(n) = \sum_{k \in \Phi} \hat{a}_{i,k} \cdot \hat{s}_k(n) \quad (5)$$

where $\hat{s}_k(n)$ is the kth estimated source signal, $\hat{a}_{i,k}$ - entry of the estimated matrix $\hat{\mathbf{A}}$, $y_{\Phi,i}(n)$ - components of the ith measured signal which are reconstructed on the basis of the chosen source subspace (Φ).

When the number of the source signals is higher than the number of the measured ones, ICA fails. In such cases, projective filtering can help to increase the number of source signals that can be separated. First the estimates composing the dominant source subspace are chosen. Then they are enhanced by the operation of projective filtering, subsequently reprojected and finally subtracted from the original measured signals

$$r_{\Phi,i}(n) = y_i(n) - \sum_{k\in\Phi} \hat{a}_{i,k} \cdot PF\{\hat{s}_k(n)\} \quad (6)$$

where $PF\{.\}$ denotes the operation of projective filtering.

By this operation the number of independent components in the residual signals ($r_{\Phi,i}(n)$, i=1, ..., K) is decreased and more source signals can be extracted by the second application of ICA.

3. RESULTS AND DISCUSSION

The developed method can be applied to fetal ECG extraction from multi-channel abdominal signals even when the number of channels is relatively low. In this study its performance was illustrated with an example of processing the four-channel abdominal signals recorded in twin pregnancy.

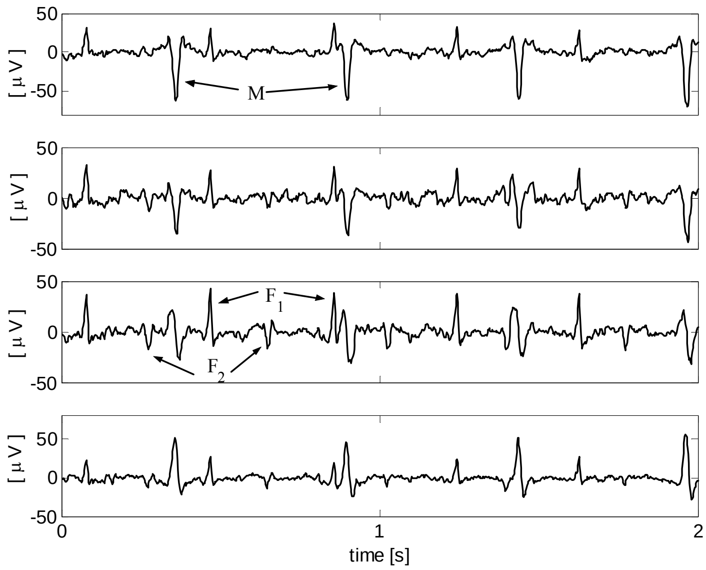

Fig.1 The measured abdominal bioelectric signals containing the MECG (M), the FECGs of two fetuses (F_1 and F_2) and some noise.

Fig.1 presents the measured signals. They are a complicated mixture of the maternal ECG and the signals of the fetal twins. Application of the JADE algorithm allowed to obtain (Fig.2) a high quality maternal ECG ($\hat{s}_1(n)$) and a high quality fetal ECG ($\hat{s}_2(n)$), but the signal of the second fetus remained mixed with the maternal ECG ($\hat{s}_3(n)$). Only two estimates of the source signals composed the maternal ECG source subspace ($\Phi = \{1,3\}$). Projective filtering allowed to enhance these estimates. Particularly important was suppression of the fetal ECG in $\hat{s}_3(n)$. Since the level of this component is comparable with the level of the maternal electrocardiogram, the following problems emerged: the difficulty to perform detection of the maternal QRS complexes, and the necessity to apply the proper dimensions of local signal subspaces to achieve both the effective suppression of the FECG and the precise reconstruction of the MECG.

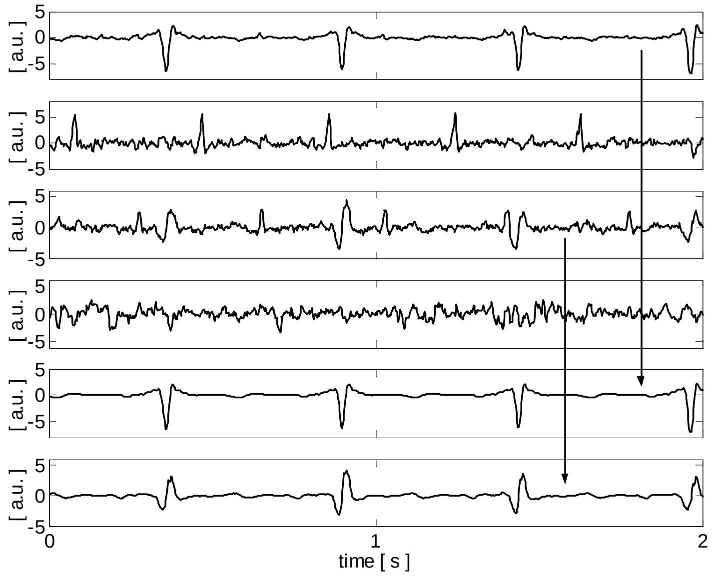

Fig.2 The source signals estimates obtained by application of the JADE algorithm, and the MECG source subspace ($\Phi = \{1,3\}$) enhanced by the operation of projective filtering. The signals (from the top: $\hat{s}_1 \div \hat{s}_4$, $PF\{\hat{s}_1\}, PF\{\hat{s}_3\}$) are presented in arbitrary units.

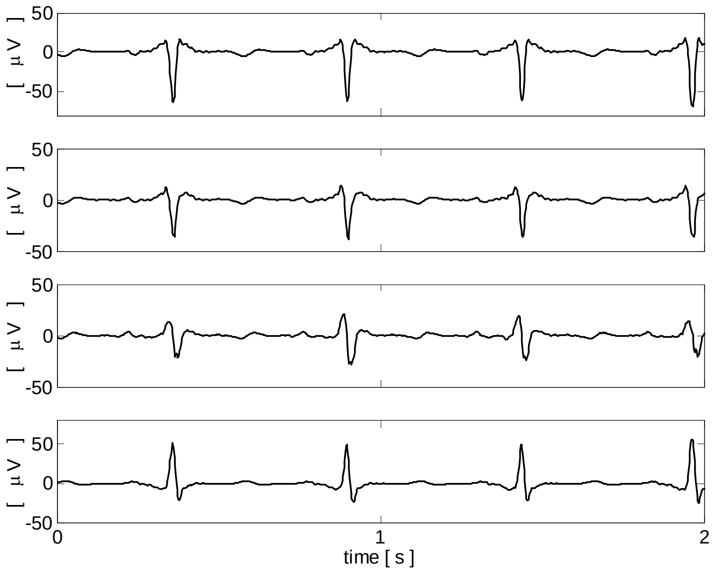

Fig.3 The reconstructed MECG component of the measured signals (compare to Fig.1).

The solution of the first problem was very simple - the results of QRS detection in $\hat{s}_1(n)$ were exploited while processing $\hat{s}_3(n)$. The solution of the second problem was more difficult. We applied the approach presented in [8] based on the varying dimensions of local signal subspaces (higher in highly variable parts of the maternal beats, but lower in more repeatable sections). As a result, a significant enhancement of the maternal ECG in the processed channels was achieved. Since the source signals estimates are scaled to be of unit variance [4], their amplitude is immaterial; therefore, they are presented in arbitrary units in Fig.2 (and Fig.5).

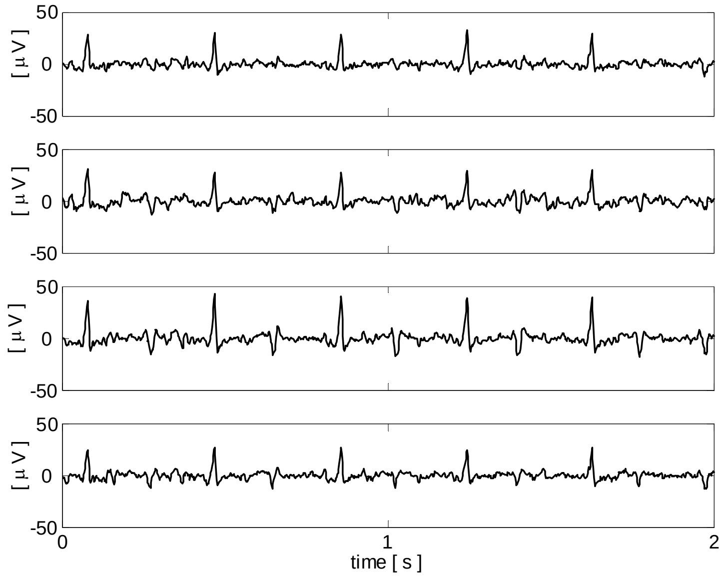

Fig.4 The fetal electrocardiograms enhanced by subtraction of the reconstructed MECG (Fig.3) from the measured signals (Fig.1).

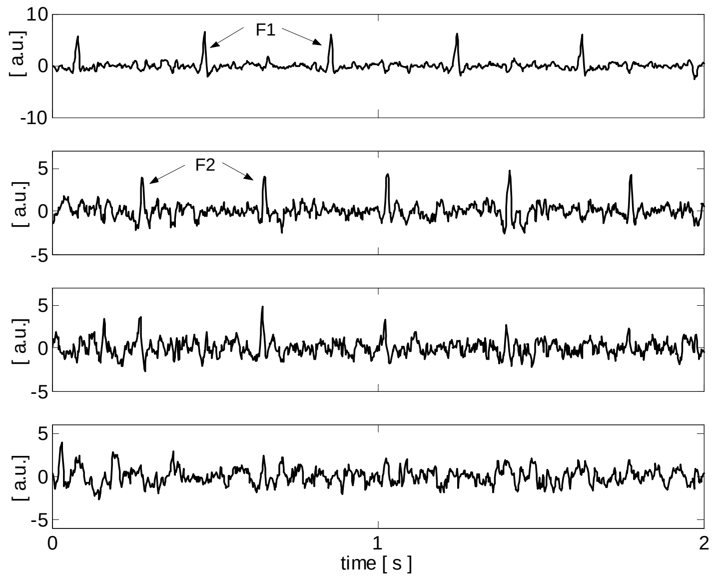

Fig.5 The ECG signals of the two fetuses (F1 and F2) separated by the second application of ICA.

Reprojecting the enhanced estimates (according to (5) with $\hat{s}_k(n)$ replaced by $PF\{\hat{s}_k(n)\}$) allowed to reconstruct the maternal electrocardiograms contained in the measured signals (Fig.3). By subtraction of these signals from the original measured ones, the maternal source subspace was suppressed and the FECG signals were enhanced (Fig.4). However, the two signals remained mixed and ICA had to be applied for the second time to separate them. This operation produced two fetal ECGs of relatively high quality (Fig.5).

In this study we analyzed the signals recorded in two cases of twin pregnancy. In the presented case, suppression of the MECG source subspace and the second application of ICA allowed to obtain the high quality ECGs of both fetuses. In the second case, however, the signal processing was completed with only a limited success. We were able to extract only one FECG - the signal of the second fetus remained hidden by noise.

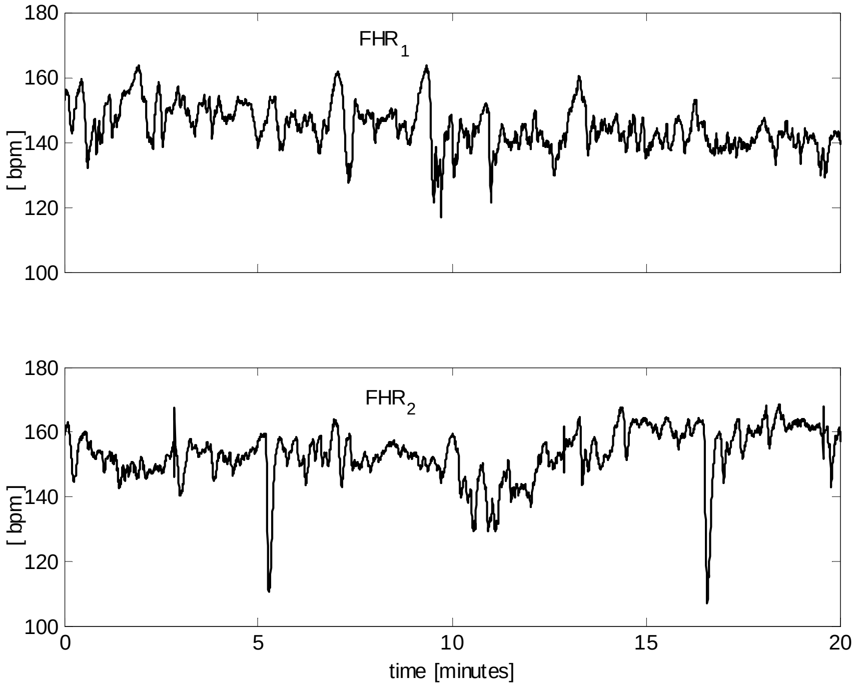

Fig.6 The FHR traces of the fetal twins.

The separated signals (the uppermost two in Fig.5) were analyzed to determine the fetal heart rate (FHR) traces of the twins. The method described in [7], based on the normalized matched filtering, was applied to perform QRS detection. The obtained RR interval sequences were converted to the FHR traces by application of the Berger's method which performs determination of the RR intervals number (with fractional parts) in a moving time window [1]. The obtained form of the FHR signals (Fig.6) is appropriate for the spectral analysis [1]; after some additional smoothing it also allows the classical analysis aimed at the FHR baseline estimation and accelerations/decelerations detection. Such analysis can also be performed on the basis of the FHR traces acquired using the Doppler ultrasound transducer. However, more sophisticated analysis, e.g. assessment of the beat-to-beat variability of the FHR traces, can most precisely be performed on the basis of the RR intervals sequences [6] which are a natural outcome of the fetal QRS complexes detector.

4. CONCLUSIONS AND FUTURE WORKS

The proposed method allows to accomplish the difficult task of separating the electrocardiographic signals of the fetal twins. In this study, contrary to most publications dealing with the problem, this ability was demonstrated on real signals of the twin pregnancy. Application of the described method allows to determine the FHR traces which can undergo both classical and more sophisticated analysis. The future works will focus on the automatic selection of the source signals that should be suppressed, and on the investigations of the method's parameters which influence the determination of the FHR traces. The developed algorithms will be implemented in the modern systems for electronic fetal monitoring.

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BIBLIOGRAPHY

[1] BERGER R.D., AKSELROD S., GORDON D., COHEN R.J., An Efficient Algorithm for Spectral Analysis of Heart Rate Variability, IEEE Trans. Biomed. Eng., Vol. 33, pp. 900-904, 1986.

[2] CALLAERTS D., DE MOOR B., VANDEWALLE J., SANSEN W., Comparison of SVD methods to extract the foetal electrocardiogram from cutaneous electrode signals, Med.&Biol.Eng.&Comput., Vol. 28, pp. 217-224, 1990.

[3] CARDOSO J.-F., Multidimensional Independent Component Analysis, Proc. ICASSP'98, Vol. IV, Seattle, WA, May 1998, pp.1941-1944.

[4] CARDOSO J.-F., SOULOUMIAC A., Blind beamforming for non-Gaussian signals, Inst. Elect. Eng. Proc.-F. Vol. 140, No.6, pp. 362-370.

[5] DE LATHAUWER L., CALLAERTS D., DE MOOR B., VANDEWALLE J., Fetal electrocardiogram extraction by source subspace separation, Proc. IEEE SP/ATHOS Workshop on HOS, Girona,pp.134-138, Spain, 1995.

[6] JEŻEWSKI J., WRÓBEL J., HOROBA K., Comparison of Doppler Ultrasound and Direct Electrocardiography Acquisition Techniques for Quantification of Fetal Heart Variability, IEEE Trans. Biomed. Eng., Vol. 53, pp. 855-864, 2006.

[7] KOTAS M., A New Method of Fetal QRS Detection, Biocybernetics and Biomedical Engineering, Vol. 16, No. 3-4,pp. 147-163, 1996.

[8] KOTAS M., Projective Filtering for Fetal ECG extraction, Bulletin of the Polish Academy of Sciences, Technical Sciences, Vol. 55, No. 4, pp. 331-339, 2007.

[9] KOTAS M., Projective Filtering of the Time-Aligned ECG Beats, IEEE Trans. Biomed. Eng., Vol. 51, pp. 1129-1139,2004.

[10] KOTAS M., Projective filtering of time-aligned ECG beats for repolarization duration measurement, Computer Methods and Programs in Biomedicine, Vol. 85, pp. 115-123, 2007.

[11] MATONIA A., JEŻEWSKI J., KUPKA T., HOROBA K., GACEK A., The influence of coincidence of fetal and maternal QRS complexes on fetal heart rate reliability, Med.&Biol.Eng.&Comput., Vol. 44, pp. 393-403, 2006.