fetal ECG, QRS detection,
dynamic time warping, embedding operation

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STATE-SPACE AVERAGING FOR MATERNAL ECG SUPPRESSION

In this paper a new method of maternal electrocardiogram suppression for fetal component extraction from one-channel maternal abdominal bioelectric signals is proposed. The method performs maternal ECG estimation by application of state-space averaging. The estimated signal is subtracted from the original one and this way suppressed. The method parameters allow us to balance between the precision of maternal ECG suppression and the necessity not to attenuate the fetal QRS complexes. A small database of the maternal abdominal bioelectric signals is used to investigate the developed system for fetal heart rate determination. The final assessment is based on the detection performance index. It is shown that by proper choice of the parameters we can tune the system so that it is more effective than the classical approach based on template subtraction.

1. INTRODUCTION

The noninvasive fetal electrocardiography, based on the analysis of the maternal abdominal bioelectric signals, is a promising technique which offers higher accuracy of fetal heart rate (FHR) monitoring than the routine approach based on the Doppler ultrasound instrumentation [3]. The most important operations that have to be accomplished for FHR determination are: maternal electrocardiogram (MECG) suppression, fetal electrocardiogram (FECG) enhancement and fetal QRS detection. In this study, we focus on the problem of MECG suppression in such a way to allow successful detection of fetal complexes. Different methods have already been proposed for this purpose. We can distinguish one-channel [1, 8] and multi-channel [1, 2] ones. Whereas the multi-channel methods use the spatial redundancy of the ECG signals to achieve the goal of maternal and fetal components separation, the one-channel approaches exploit the repeatability of ECG beats. We propose a new one-channel method. It is based on a classical scheme: estimation of the MECG component and then its subtraction. For MECG estimation a modified version of a simple nonlinear state-space filtering [6, 9] is applied. The method performs reconstruction of the state-space representation of the processed one-dimensional signals, then determination of neighbourhoods of state-space vectors and, finally, averaging of central coordinates of the vectors. This way it enables enhancement of the repetitive MECG component preserving the individual beats deviations from the average one. Simultaneously, it leads to effective suppression of the other signal components. Finally, the operation of subtraction leads to MECG suppression and fetal ECG extraction.

2. METHODS

2.1. STATE-SPACE AVERAGING (SSA)

The name of state-space averaging was used to call the approach proposed as a very simple method for reducing noise in the data with the nonlinear time evolution [9]. The main steps proposed in [9] are as follows:

– construction of embedding space vectors:

$$\mathbf{x}^{(n)} = [x(n-N_L), \ldots, x(n+N_R)]^T \tag{1}$$

where N_L and N_R are fixed positive integers, x(n) – the analyzed one-dimensional time series.

– the search for neighbourhoods of the respective state-space points (vectors)

$$\Gamma^{(n)} = \left\{ k \mid \left\| \mathbf{x}^{(k)} - \mathbf{x}^{(n)} \right\| < \varepsilon \right\} \tag{2}$$

where ε is the chosen radius of the neighbourhoods, *k* - the time indices of the points included into the neighbourhood.

– replacing the 0*th* coordinate $\mathbf{x}_0^{(n)}$ of each state space vector (corresponding to $x(n)$) by the average within the neighbourhood

$$x'(n) = \sum_{k \in \Gamma^{(n)}} \mathbf{x}_0^{(k)} \tag{3}$$

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where x'(n) is the corrected sample of the processed time series.

In this study we apply the symmetric embedding ($N_L = N_R$). Setting $m = N_L+N_R = 2*N_L$ we obtain

$$\mathbf{x}^{(n)} = [x(n-\tfrac{m}{2}), \ldots, x(n+\tfrac{m}{2}]^T \qquad (4)$$

where the embedding dimension is equal to m+1.

Since the proper value of m depends on the applied sampling frequency, it is advantageous to define the so called embedding window τ_m determining the interval covered by the embedding vectors.

2.2. DYNAMIC TIME-WARPING FOR NEIGHBORHOODS DETERMINATION

As in the method of projective filtering of time warped ECG beats [4, 5], in this study we have also applied the method of dynamic time warping to the construction of neighbourhoods. The operation of SSA is preceded with linear filtering for baseline wander and power line interference suppression, QRS complex detection, and cross-correlation function based synchronization of the detected complexes. The last operation produces a set of fiducial marks $\{r_k \mid k=1,2,\ldots, K\}$ corresponding to the same position within the respective detected QRS complexes.

The embedding space points are divided into successive, slightly overlapping sequences of vectors whose time indices belong to the following sets

$$\Psi_k = \{\, a_k + l \;\mid l = 0,1, ..., N_k \,\}, \quad k = 1, 2, ..., K-1 \qquad (5)$$

where $a_k = r_k - b$, $N_k = r_{k+1} - r_k + 2b$; b is a small positive integer introduced to immunize the method against small errors of the fiducial marks determination (as in [5]).

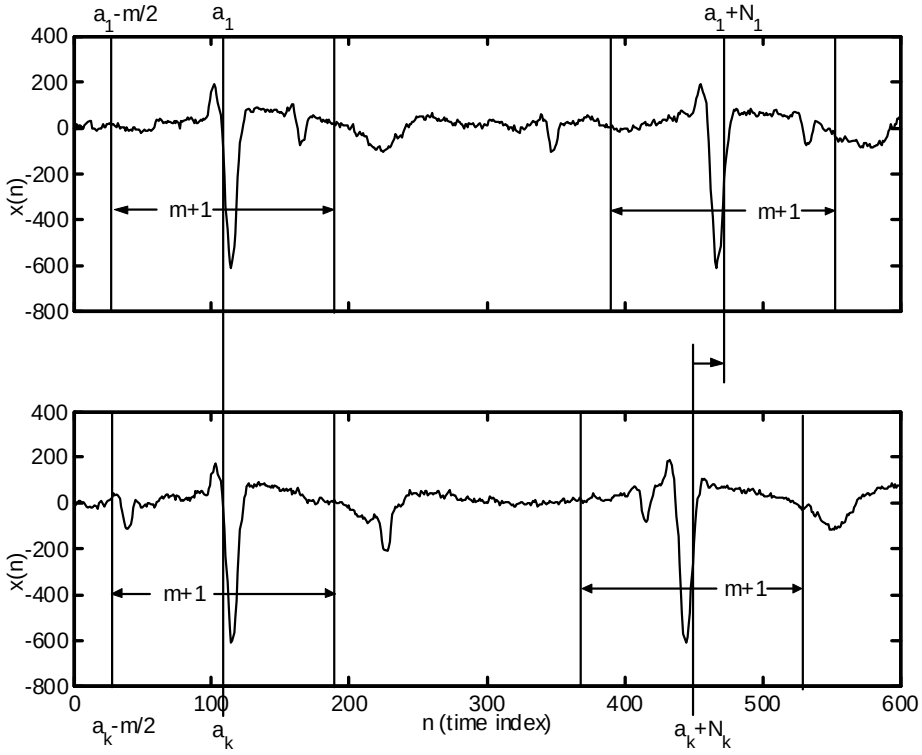

Fig. 1. The ECG signal sections containing successive QRS complexes. The presented embedding windows show the first and the last state-space points of Ψ_1 and Ψ_k respectively. The kth sequence of points is time warped with respect to the first one

The general concept [5] is to perform the nonlinear alignment of the successive sequences of vectors (Ψ_k, k = 2, 3, ... K-1) with respect to the first sequence and this way to determine the neighbourhoods corresponding to the respective positions within Ψ_1.

For small b the side points $\mathbf{x}^{(a_1)}$ and $x^{(a_1+N_1)}$ overlap QRS complexes (as in Fig.1), and thus their neighbourhoods can be determined on the basis of the preprocessing step results:

$$\Gamma^{(a_1)} = \left\{ a_k \;\middle|\; k = 1,2,...,K-1 \right\}$$
$$\Gamma^{(a_1+N_1)} = \left\{ a_k + N_k \;\middle|\; k = 1,2,...,K-1 \right\} \tag{6}$$

Determination of the neighbourhoods corresponding to the respective positions within Ψ_1 is performed in the following way [5].

1. In the first step each neighbourhood of a point from Ψ_1 is filled with this point only, and so the time index of this point is included into the neighbourhood set

$$\Gamma^{(a_1+l)} = \left\{ a_1 + l \right\}, \quad l = 0,1,...,N_1 \tag{7}$$

These points become the first mass centres of the respective neighbourhoods. Then we set $k = 2$ and go to the next step.

2. The sequences of points that belong to Ψ_k are time warped with respect to the sequence of the mass centres. For this purpose, the so-called warping paths are calculated: $w_{k,l}$, $l = 0, 1, ..., N_1$, containing the indices of the vectors $\mathbf{x}^{(a_k+w_{k,l})}$ that are aligned with the successive mass centres $\bar{\mathbf{x}}^{(a_1+l)}$. The warping path is calculated by minimizing

$$Q_k = \sum_{l=0}^{N_1} \left\| \mathbf{x}^{(a_k+w_{k,l})} - \bar{\mathbf{x}}^{(a_1+l)} \right\| \tag{8}$$

while preserving the border conditions, the monotonicity conditions and the condition restricting the number of successive points from Ψ_k that may be omitted in the warping path [5].

3. After the kth sequence Ψ_k has been time warped with respect to the sequence of the mass centres, the neighbourhoods are supplemented with the points whose indices are stored in the warping path

$$\Gamma^{(a_1+l)} = \Gamma^{(a_1+l)} \cup \left\{ a_k + w_{k,l} \right\} \tag{9}$$

4. The mass centres of the respective neighbourhoods are updated and k is incremented. If $k < K$-1 we go to step 2, otherwise we end the algorithm.

Each constructed neighbourhood contains the points (signal intervals) that occupy the same position within the nonlinearly aligned sequences of vectors. To reconstruct the central coordinates of the respective vectors (according to (3)), for each vector $\mathbf{x}^{(a_k+w_{k,l})}$ we determine the smaller neighbourhood – as the assumed percentage of the nearest among the points contained in $\Gamma^{(a_1+l)}$. To this end, we calculate the distances from $\mathbf{x}^{(a_k+w_{k,l})}$ to the respective points from $\Gamma^{(a_1+l)}$, we sort the distances and we accept round($c_A \cdot \left|\Gamma^{(a_1+l)}\right|$) of the nearest points; | ... | denotes cardinality of a set; $0 < c_A \leq 1$.

2.3. THE SYSTEM FOR FETAL HEART RATE DETERMINATION

The method of state-space averaging was successfully applied [4] to ECG signals processing for wide-band noise suppression. In this study, it is applied to maternal ECG estimation. As it is shown in Fig. 2, the estimated MECG is subtracted from the original signal to extract the fetal ECG. The obtained signal is analyzed by a detector of fetal QRS complexes, and, as a result, the locations of the complexes are determined.

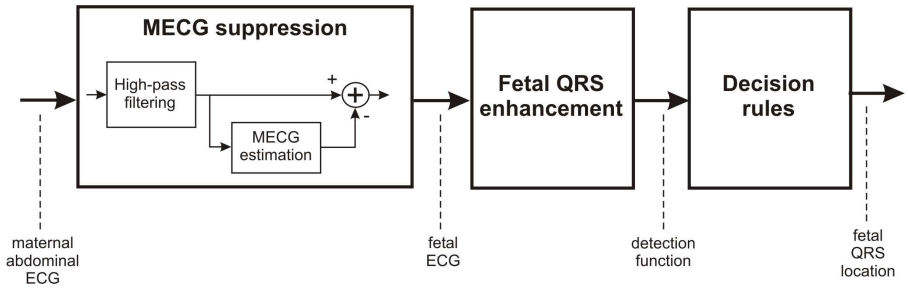

Fig. 2. The block diagram of a single-channel system for fetal heart rate determination

The applied detector consists of linear band-pass filtering for noise attenuation, differentiation for QRS slopes estimation, and squaring and moving window integration. This way we form a so called detection function which responds with distinctive peaks to fetal QRS complexes. The detection function is compared with automatically calculated detection

threshold. Once a peak crosses the threshold, we search for higher peaks within a 250 ms interval. Each encountered higher peak replaces the previous one. The search is stopped when no higher peak is found within the specified time interval. The found highest peak is stored as the QRS location and the search for the next complexes is continued. More detailed description of the algorithm can be found in [7].

3. RESULTS

To evaluate the system, we used ten four-channel maternal abdominal bioelectric signals with the established locations of the fetal QRS complexes. Each signal was five minutes long. During tests the respective channels were used as different one-channel signals. The obtained detection results were evaluated with the following performance index

$$PI = \frac{N - N_{FA} - N_M}{N} \cdot 100[\%] \qquad (10)$$

where N is the total number of QRS complexes in the test signals, N_{FA} – the number of false alarms, and N_M – the number of missed complexes.

Table 1. Detection performance index obtained for different combinations of the parameters τ_m and c_A. For reference the index obtained after MECG suppression by template subtraction (TS) is given.

Parameters\Method	SSA	SSA	SSA	SSA	TS
τ_m [ms]	200	200	500	500	-
c_A [1]	0.5	1.0	0.2	1.0	-
PI *[%]*	86.2	81.9	90.4	83.3	89.0

The most important parameters that influence the proposed system performance are the embedding window τ_m and the fraction c_A of the state-space vectors accepted during determination of neighbourhoods. In the experiment, we applied the embedding window τ_m varying from 100 ms to 500 ms with the step of 100 ms. For each embedding dimension we tested the c_A parameter varying from 0.1 to 1.0 with the step 0.1. The performance indices obtained for a few combinations of these parameters are presented in Table 1.

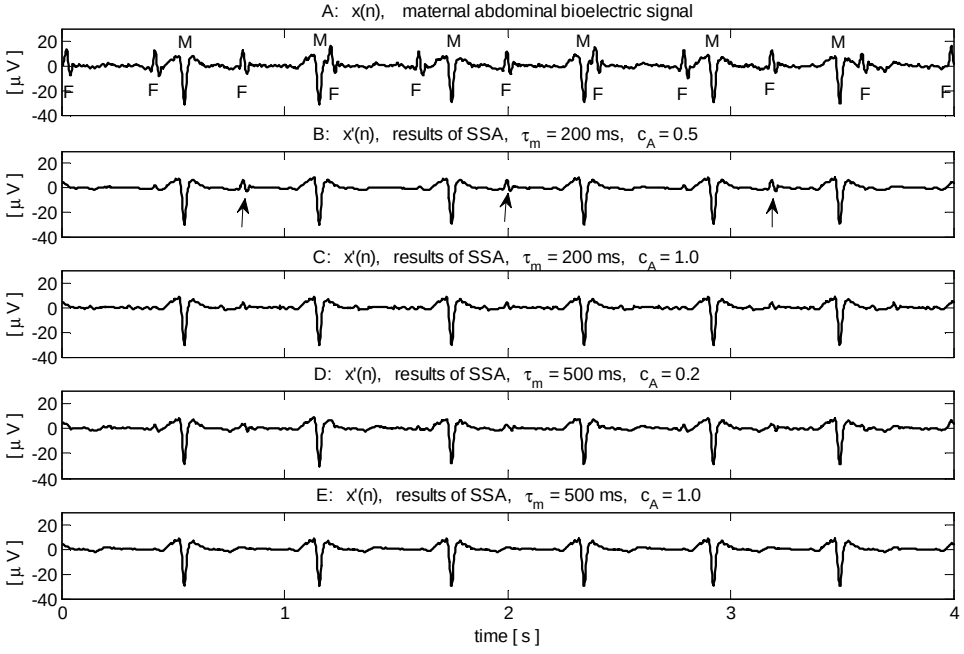

Fig. 3. Results of maternal ECG estimation by application of state-space averaging (SSA). M denotes the maternal QRS complexes, F – the fetal ones; the arrows indicate residua of the latter

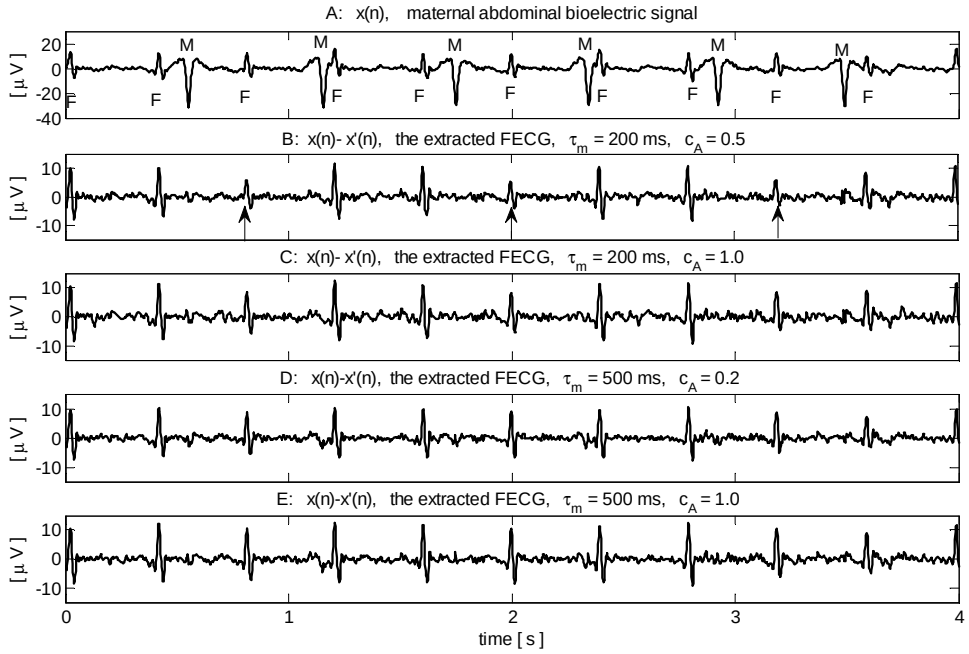

Fig. 4. The fetal electrocardiogram extracted by subtraction of the estimated MECG (the case of high level FECG component). F, M - as in Fig.3; the arrows indicate the suppressed fetal QRS complexes (compare to Fig.3.B)

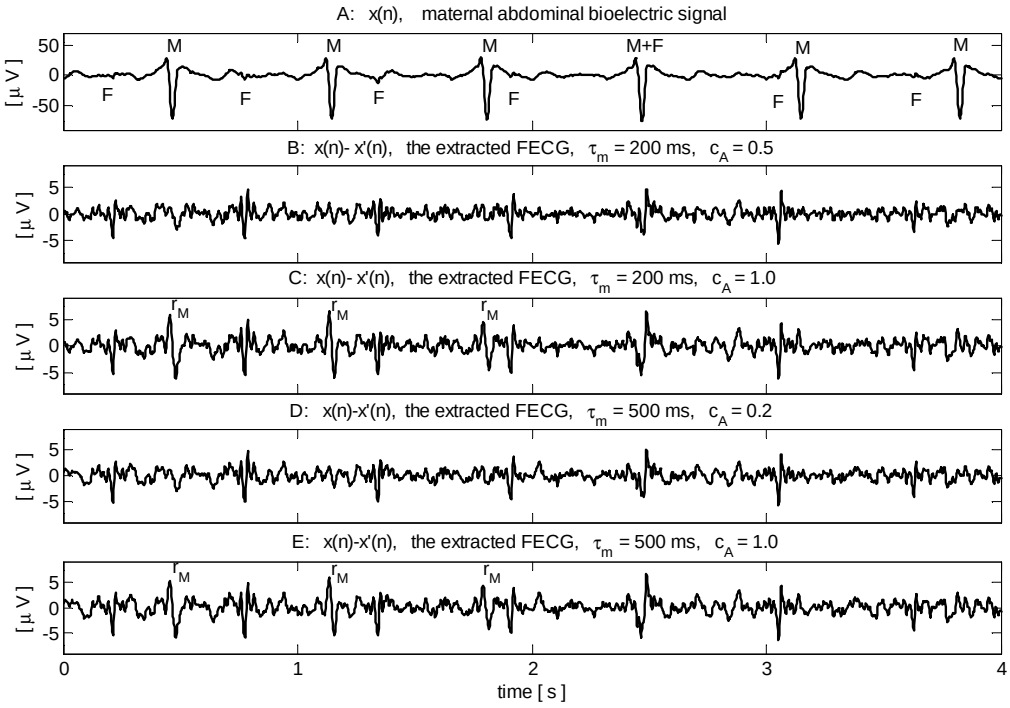

Fig. 5. The fetal electrocardiogram extracted by subtraction of the estimated MECG (the case of low level FECG component). F, M – as in Fig.3; r_M denotes residua of the maternal QRS complexes

We can notice that better results were achieved for longer embedding window. Since for so high embedding dimension most state-space vectors overlap the maternal QRS complexes, it assures more effective determination of neighbourhoods.

Although the ECG signal morphology is approximately repeatable, it is not constant. Therefore after the nonlinear alignment of the ECG signal segments according to the algorithm described, it is advantageous not to average central coordinates of all state-space vectors, but to choose those which are nearest to the corrected ones. As a result, both for τ_m=200 ms and τ_m=500 ms the highest performance indices were achieved for $c_A < 1.0$.

These observations are confirmed visually by figures 3-5. In Fig.3 we can notice that for small embedding dimension estimation of maternal ECG by SSA was not perfect. For so high level of the fetal ECG the obtained estimate contained high

residua of the fetal QRS complexes. Subtraction of such a signal according to the diagram from Fig.2 leads to inconvenient attenuation of the fetal complexes. This phenomenon is well visible in Fig.4 B.

When the level of the fetal component is low, the described effect is negligible (see Fig.5). However, it is more important to suppress precisely the maternal ECG. In Fig.5 we can notice that both for τ_m=200 ms and τ_m=500 ms when c_A=1.0, estimation of MECG signal morphology is not accurate (which results from averaging of state-space vectors that belong to the beats of possibly slightly different morphology) and after the operation of subtraction the obtained signals contain not only the fetal ECG but also the residua of the maternal complexes. Such residua complicate the further analysis of the signals which results in lower detection performance (as presented in Table 1). The highest *PI* was obtained for τ_m=500 ms and c_A=0.2. It was higher than that achieved after application of the improved method of template subtraction [8]. We can conclude that the proper choice of τ_m and c_A allows us to balance the requirement to suppress precisely the maternal ECG with the necessity not to attenuate the fetal component.

4. CONCLUSIONS AND FUTURE WORKS

The proposed method allows relatively effective suppression of the maternal ECG with limited attenuation of the fetal QRS complexes. As a result, followed by a detector of fetal complexes it enables relatively high detection performance. Compared to the classical approach based on template subtraction, it achieved higher performance index. Thus we can expect it to be an effective tool for fetal heart rate monitoring system. However, more experiments with larger databases of maternal abdominal bioelectric signals are necessary to confirm these results.

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BIBLIOGRAPHY

[1] CALLAERTS D., De MOOR B., VANDEVALLE J., et al., Comparison of SVD methods to extract the foetal electrocardiogram from cutaneous electrode signals, Med Biol Eng Comp, 1990, pp 217-224.
[2] 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, Spain, 1995, pp.134-138.
[3] 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, 2006, pp. 855-864.
[4] KOTAS M., Application of dynamic time warping to ECG processing, Proc. Int. Conf. MIT, Poland, IX 2006, pp. 169-175.
[5] KOTAS M., Projective filtering of time warped ECG beats, Computers in Biology and Medicine, Vol. 38, No. 1, pp. 127-37.
[6] KOTAS M., Combined application of independent component analysis and projective filtering to fetal ECG extraction, Biocyb. Biomed. Eng., vol. 28, 2008, pp. 75-93.
[7] KOTAS M., JEŻEWSKI J., KUPKA T., HOROBA K., Detection of low amplitude fetal QRS complexes, Proc. of 30th IEEE/EMBS Conf., 2008, pp. 4764-4767.
[8] MATONIA A., JEŻEWSKI J., HOROBA K., GACEK A., The Maternal ECG Suppression Algorithm for Efficient Extraction of the Fetal ECG from Abdominal Signal, Proc. IEEE EMBS Conf., New York City, USA, 2006, pp. 3106-3109.
[9] SCHREIBER T., Extremely simple nonlinear noise-reduction method, Physical Review E, Vol.47, No. 4, 1993, pp. 2401-2404.