

Spatio-Temporal FIR Filter for Fetal ECG Extraction

Marian Kotas, Jakub Błaszczyk, and Tomasz Moron

Abstract—In this paper we propose to apply spatio-temporal filtering to fetal ECG extraction from the multichannel maternal abdominal bioelectric signals. The method performs weighted addition of the assumed number of time samples of the respective measured signal channels. The filter weights are calculated during the learning phase of the method. After this learning phase, the filter operation is very simple, similar to usual filtering, nevertheless extraordinarily effective. Our experiments show that it can simultaneously accomplish maternal ECG suppression and fetal QRS complexes enhancement for their detection. The detection tests are performed to show the method influence on this crucial operation.

Index Terms—Fetal electrocardiogram, maternal ECG suppression, spatio-temporal filtering, generalized eigendecomposition.

I. INTRODUCTION

The noninvasive fetal electrocardiography is based on the bioelectric signals recorded from the maternal abdominal wall. Such signals contain the fetal ECG (FECG), the maternal electrocardiogram (MECG) and various types of noise. Since the maternal signal is, in most cases, of much higher level than the fetal one, the first operation which should be performed is the maternal ECG suppression.

Two the most important approaches to the problem can be distinguished. The first one exploits the repeatability of ECG beats to achieve the goal [1]. The second is based on the analysis of multichannel signals. In [2] an application of adaptive filtering was described, with a few thoracic signals at the reference inputs, combined to cancel the maternal ECG in the abdominal signals. In [3] a weighted addition of four or more abdominal signals was calculated to suppress the maternal ECG. 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 [4].

Application of not only the second (as in [4]), but also of higher order statistical conditions of independence allowed to achieve a great progress in the accomplishment of the separation task [5]. All the mentioned techniques [2], [3], [4], [5] utilize the redundancy of the multichannel ECG recordings.

However, the experiments presented in [6] showed that

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when only a few channels were recorded, it was more advantageous to apply the single-channel approach (based on template subtraction [1]).

In [7] a single channel method was applied to suppress maternal ECG in the respective channels of the signal recorded, and then spatio-temporal filtering (STF) was applied to enhance the fetal ECG extracted. In this paper we propose to apply STF simultaneously to maternal ECG suppression and fetal ECG enhancement.

II. METHODS

A. Independent Component Analysis

The method (ICA) exploits the so-called "blind source separation" model which is based on the assumption that the signals from different leads are different linear combinations of the same source signals, independent from one another

$$\mathbf{x}(n) = \mathbf{A}\mathbf{s}(n) + \mathbf{z}(n) \quad (1)$$

where $\mathbf{x}(n)=[x_1(n), \dots, x_k(n)]^T$ denotes the observation vector in the measurement space (the measured signals vector), $\mathbf{s}(n)=[s_1(n), \dots, s_k(n)]^T$ is the source signals vector, $\mathbf{z}(n)=[z_1(n), \dots, z_k(n)]^T$ the vector of the noise components; $\mathbf{A}$ is the mixing (projecting) matrix. For simplicity the same number of measured and source signals, equal to K , is assumed in the model.

Knowing the projecting matrix $\mathbf{A}$ and assuming that it can be inverted, we could calculate the separating matrix $\mathbf{B}=\mathbf{A}^{-1}$ and then decompose the measured signals as follows

$$\hat{\mathbf{s}}(n) = \mathbf{B}\mathbf{x}(n)\mathbf{A}^{-1} = \mathbf{A}\mathbf{s}(n) + \mathbf{A}^{-1}\mathbf{z}(n) = \mathbf{s}(n) + \mathbf{z}'(n) \quad (2)$$

where $\mathbf{z}'(n)=\mathbf{A}^{-1}\mathbf{z}(n)$. However, since $\mathbf{A}$ is usually unknown, we have to perform the "blind source separation", only on the basis of the source signals statistical independence.

To this end, in our study we apply the JADE algorithm, exploiting the second and the fourth order conditions of the statistical independence for separating matrix estimation [8].

B. Spatio-Temporal Filtering

To suppress the maternal ECG and enhance the FECG, we perform the following summation:

$$f_{STF}(n) = \sum_{i=1}^K \sum_{j=-J}^J c_{i,j} f_i(n + j \cdot \tau) \quad (3)$$

i.e. we add $2J+1$ time samples of the K channels ($i=1, \dots, K$) of the bioelectric signals from the maternal abdomen. Since the finite number of the time samples of the signals from different leads are summed, the operation can be called as

spatio-temporal finite impulse response (FIR) filtering.

Defining an extended signal vector [7]:

$$\mathbf{f}(n) = \begin{bmatrix} f_1(n - J \cdot \tau) \\ \vdots \\ f_K(n - J \cdot \tau) \\ f_1(n + J \cdot \tau) \\ \vdots \\ f_K(n + J \cdot \tau) \end{bmatrix} \quad (4)$$

we can express the operation of spatio-temporal filtering in a matrix notation:

$$f_{STF}(n) = \mathbf{c}^T \mathbf{f}(n) \quad (5)$$

where $c_i, i=1, 2, \dots, (2J+1)K$ are the weights of the spatio-temporal FIR filter (in the experiments that will be presented $J = 3$ and $\tau = 4$ have been used).

The operation can be regarded as the projection of the extended signal vector on the direction $\mathbf{c}$ which should assure the maximal ratio of the signal-to-noise. Here we consider the fetal QRS complexes as the signal to be enhanced, and all other signal components (also the maternal ECG) as noise. To determine $\mathbf{c}$ we have to find the signal segments of relatively high SNR to represent the desired component (the fetal QRS complexes) and the segments of much lower SNR to represent noise.

If we gather the desired signal segments in matrix $\mathbf{A}(K \times N_A)$ and the noise segments in matrix $\mathbf{B}(K \times N_B)$ (where N_A and N_B denote the number of the desired signal samples and the noise component samples, respectively), we can write the objective function to be maximized in the following way:

$$\mathbf{Q}(\mathbf{c}) = \frac{\frac{1}{N_A} \|\mathbf{c}^T \mathbf{A}\|^2}{\frac{1}{N_B} \|\mathbf{c}^T \mathbf{B}\|^2} = \frac{N_B}{N_A} \frac{\mathbf{c}^T \mathbf{A} \mathbf{A}^T \mathbf{c}}{\mathbf{c}^T \mathbf{B} \mathbf{B}^T \mathbf{c}} = \frac{\mathbf{c}^T \mathbf{R}_A \mathbf{c}}{\mathbf{c}^T \mathbf{R}_B \mathbf{c}} \quad (6)$$

where $\|\cdot\|$ denotes the Euclidean distance; $\mathbf{R}_A$ and $\mathbf{R}_B$ are the covariance matrices of the desired signal and the noise, respectively.

C. Estimation of STF Filter Weights

To maximize the objective function (6) we search for its stationary points, satisfying:

$$\frac{\partial \mathbf{Q}(\mathbf{w})}{\partial \mathbf{w}} = \mathbf{0} \quad (7)$$

This way we obtain [7]:

$$\mathbf{R}_A \mathbf{w} = \frac{\mathbf{w}^T \mathbf{R}_A \mathbf{w}}{\mathbf{w}^T \mathbf{R}_B \mathbf{w}} \mathbf{R}_B \mathbf{w} = \mathbf{Q}(\mathbf{w}) \mathbf{R}_B \mathbf{w} \quad (8)$$

which is equivalent to the generalized eigendecomposition equation:

$$\mathbf{R}_A \mathbf{w} = \lambda \mathbf{R}_B \mathbf{w} \quad (9)$$

and the values of $\mathbf{Q}(\mathbf{w})$ at the stationary points are the generalized eigenvalues λ_i of this equation. The corresponding vectors $\mathbf{w}_i$ are the generalized eigenvectors of the decomposition. Thus the generalized

eigenvector corresponding to the greatest eigenvalue assures the maximal signal-to-noise ratio (as defined by (6)).

Estimation of the weights can be called as the learning phase of spatio-temporal filtering.

D. Signal and Noise Segments

The signal segments to be enhanced should be located within or closely to the fetal QRS complexes. The segments to be suppressed should be located between these complexes and should not overlap them. Our initial experiments showed that the latter requirement can be relaxed. Because of the MECG dominance, inclusion of a small number of these complexes should not change the estimated covariance matrix $\mathbf{R}_B$ much. To determine matrices $\mathbf{A}$ and $\mathbf{B}$, initial detection of fetal QRS complexes should be performed.

E. Initial Detection of Fetal QRS Complexes

For this purpose the following operations are executed:

- 1) Linear band-stop filtering for powerline interference and low frequency components suppression.
- 2) Detection of the maternal QRS complexes (with the use of the multichannel detection function [9]).
- 3) Blanking (replacing with zeros) of the maternal complexes in all channels of the signal processed.
- 4) Enhancement of fetal QRS complexes by application of independent component analysis and selection of the source signal estimate dominated by these complexes (a method based on the analysis of the autocorrelation function has been developed for this purpose).
- 5) Detection of fetal QRS complexes in the signal selected (the detection function responding with distinct peaks to QRS complexes and the modified decision rules described in [10] are used).

After determination of the fetal complexes locations $r(i), i=1, \dots, I$ (I is the number of the complexes detected) the signal samples within the limits $r(i) - u \leq n < r(i) + u$ are gathered in matrix $\mathbf{A}$, whereas the samples occurring between the successive complexes $r(i-1) + o \leq n < r(i) - o, i=2, \dots, I$, in matrix $\mathbf{B}$ (in the experiments that will be presented the values $u = 8$ and $o = 50$ have been used).

III. NUMERICAL EXPERIMENTS

In our experiments we have used five records from the Physionet database of abdominal and direct fetal electrocardiogram ADFECG [11], [12]. They are denoted as r01, r04, r07, r08 and r10. Each record contains four-channel maternal abdominal traces, a simultaneously recorded direct fetal ECG and the reference locations of the fetal QRS complexes (the signals, originally stored with the sampling frequency of 1000 Hz, were decimated by a factor of 2).

A. Qualitative Results

In this paragraph we present results of the most important stages of signal processing of the method proposed and the reference results obtained with the use of ICA. The four-channel signal (r07) after suppression of powerline interference and low frequency components is presented in Fig. 1 As we can see, the signal is of relatively high quality, with predominant maternal ECG but also with distinct fetal QRS complexes. However, in Fig. 2 we can notice that

although these complexes are so well visible, they could not have been separated from the maternal ECG with the use of independent component analysis. The simplest way to remove the maternal ECG is to replace its QRS complexes with zeroes. This operation is called as blanking. It is performed in the third step of the algorithm for initial detection of fetal QRS complexes. Of course, as we can see in Fig. 3, this operation removes not only the maternal complexes but also the fetal ones if they are too close to those maternal. However, usually the number of fetal complexes removed is negligible and detection of the remaining ones should be sufficient for estimation of STF weights. In the signal presented, in three signal channels the amplitudes of the fetal complexes are rather high, satisfactory for the purpose of their detection. However, it can be advantageous to enhance these complexes with the use of independent component analysis. As we can see in Fig.4, the method managed to achieve this goal. The first estimate of the source signal contains high quality FECG. This estimate was selected and processed for initial detection of fetal QRS complexes, determination of matrices **A** and **B** and finally estimation of STF weights.

The operation of the created spatio-temporal FIR filter is illustrated in Fig. 5. Whereas the upper subplot presents one of the four abdominal signals, the lower one shows the extracted FECG. As we can see, the proposed method allowed for successful suppression of the maternal ECG and at the same time for enhancement of the fetal QRS complexes.

In the example presented, the processed signals are of relatively high quality, and even before spatio-temporal filtering we can easily distinguish fetal QRS complexes when they are not overlapping with the maternal ones. While processing the maternal abdominal signals, we usually have to face more difficult problems, such as for example occurrences of so called bursts of noise whose amplitude significantly exceeds that of the fetal complexes. In Fig. 6, we have presented a signal with the simulated burst of noise. The noise was generated by autoregressive low pass filtering of the random numbers of Gaussian distribution. This way we obtained the most troublesome noise, with the frequency spectrum overlapping that of the fetal QRS complexes. We can see that after addition of this noise to the abdominal signal not only the fetal QRS complexes have vanished but the maternal ones have become hardly discernible as well.

To process the signal successfully, we slightly modified the learning phase of STF. After the initial detection of the fetal QRS complexes, we filled matrix **A** with the desired fetal complexes, but instead of filling matrix **B** as it was described in subsection 2.5, we filled it with the whole signal segment presented in Fig.6 (containing not only the noise but the desired fetal ECG as well).

Maximizing objective function (6), we simultaneously try to maximize its numerator and minimize the denominator. By maximizing numerator, we prevent suppression of the fetal QRS complexes which would happen if only denominator of (6) was minimized.

Thus by simultaneous maximizing the numerator and minimizing the denominator, we managed to develop a filter that was able to suppress the maternal ECG and the troublesome burst of noise, and to enhance the fetal QRS complexes (Fig. 7). As a result, the constructed detection

function responds with easily discernible peaks to all the fetal QRS complexes presented.

The example with a sudden burst of noise shows that if we know the desired component shape or if there exist signal parts where it can be distinguished from noise, we can successfully tackle the problem of its detection in signal parts with the excessive amount of noise.

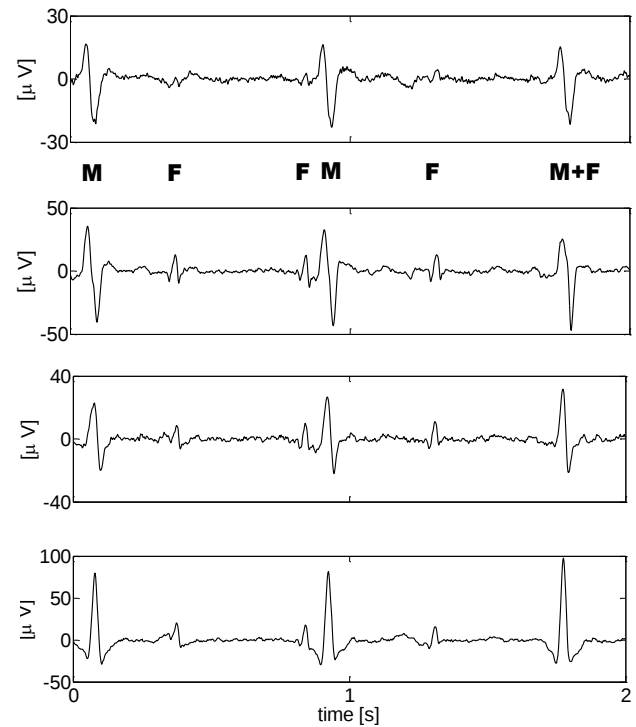


Fig. 1. Four simultaneously recorded channels of the maternal abdominal bioelectric signals. Each channel contains the maternal electrocardiogram, the fetal electrocardiogram and some noise. Locations of the maternal and the fetal QRS complexes are marked with M and F, respectively. M+F denotes the case of the complexes overlapping.

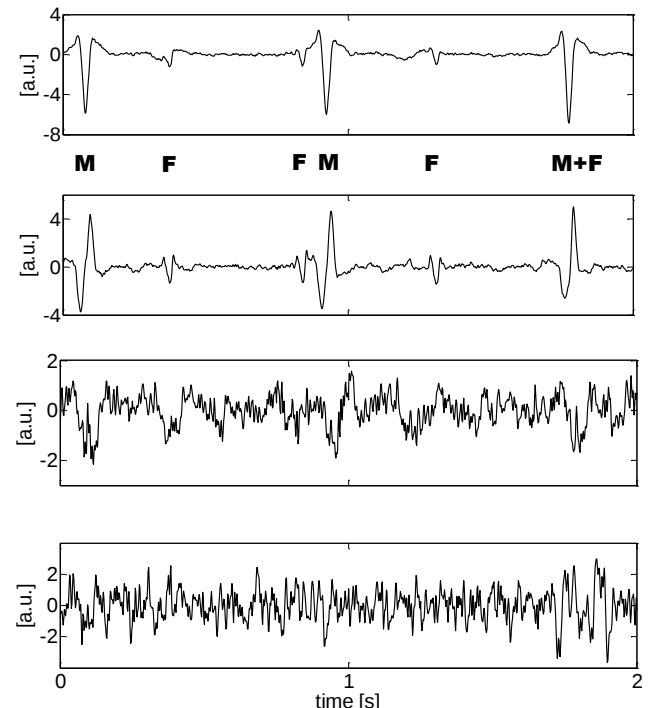


Fig. 2. Four source signals estimates obtained by application of independent component analysis to the signals from Fig. 1. F, M as in Fig. 1; a.u. denotes arbitrary units.

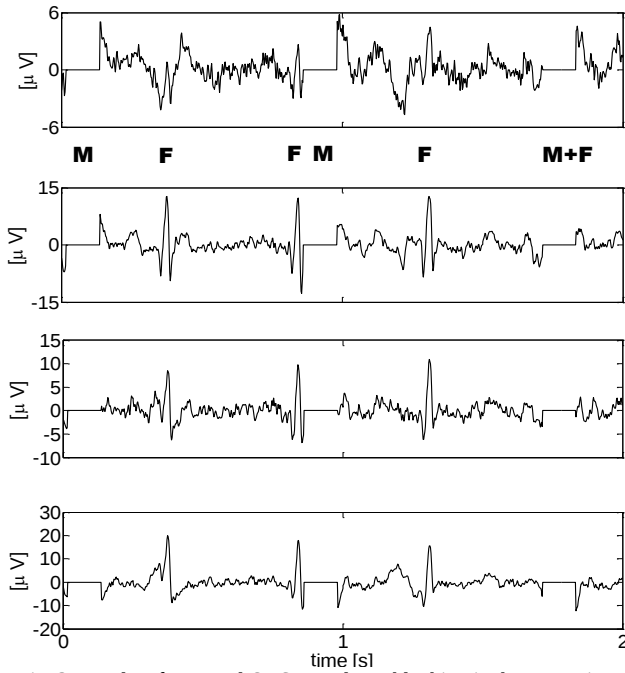


Fig. 3. Results of maternal QRS complexes blanking in the respective channels of the signals from Fig. 1. F, M as in Fig. 1.

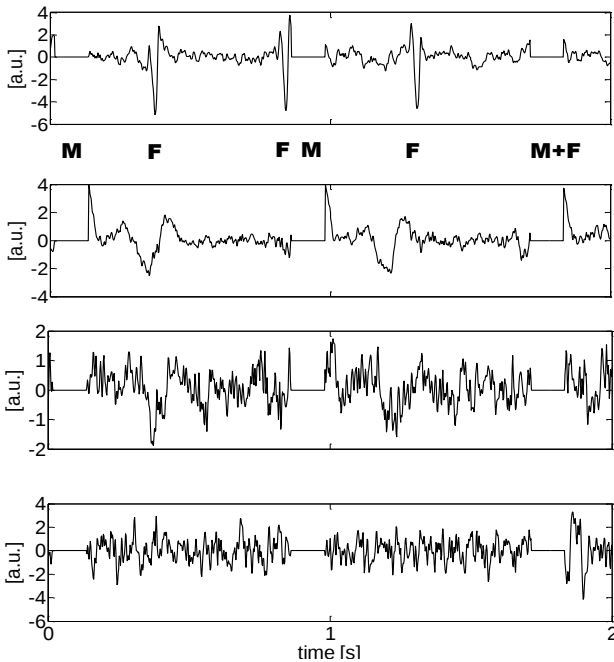


Fig. 4. Four source signals estimates obtained by ICA when applied to the signals from Fig. 3. F, M, a.u. as in Fig. 2.

B. Quantitative Results

The operation of spatio-temporal filtering of the maternal abdominal signals has been developed for the purpose of fetal QRS complexes detection. Therefore in this section we present the results of the detection tests. The tests were performed on 5 records from the ADFECG database. In each record the initial part of 60 s was used for estimation of STF weights, and then the whole signal underwent STF filtering and fetal QRS detection (with the use of the same detection function and detection rules as during the initial detection). The determined positions of the complexes were compared to the reference ones and the numbers N_{FN} of false negative and N_{FP} of false positive detections were established (for all signals the detection results occurring in the beginning and

ending intervals of 1 s were neglected, and since in the r10 record the direct FECG was lost between 187 and 191 s, and between 203 and 211 s of the trace, in these parts of the signal they were neglected as well). The N_{FN} and N_{FP} numbers are presented in Table I. For reference the analogous results obtained for the FECG signals extracted with the use of independent component analysis or the modified method of template subtraction (TS) [7] are provided.

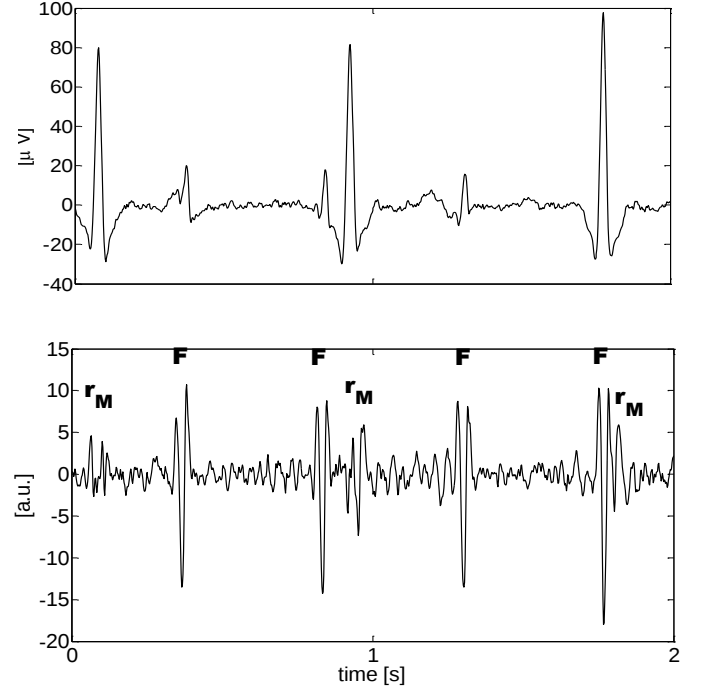


Fig. 5. Results of STF filtering. The upper subplot presents the 4th channel of the signal from Fig. 1. Below is the signal obtained with the use of STF. The enhanced fetal QRS complexes are marked with F and the residuals of the maternal ones, with rM.

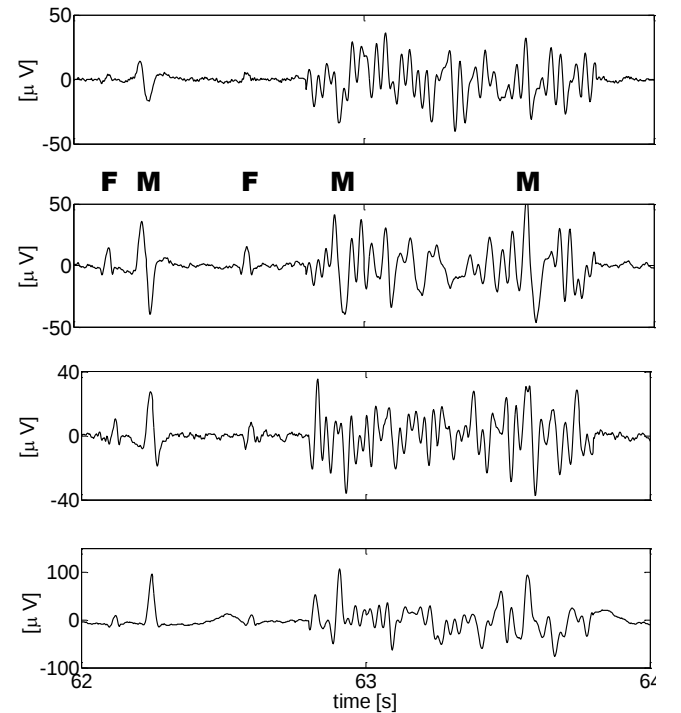


Fig. 6. Four channels of the maternal abdominal bioelectric signals: the simulated case of a sudden burst of noise. Locations of the discernible QRS complexes are marked with M and F as before.

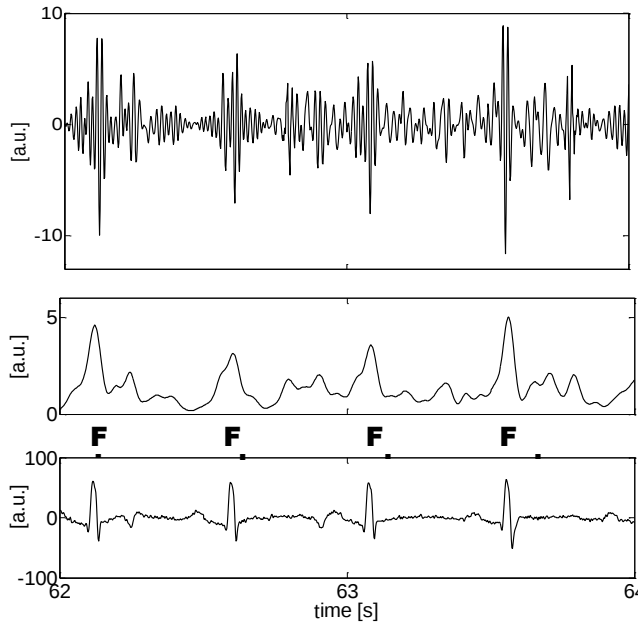


Fig. 7. From the top: results of STF filtering in the case of a sudden burst of noise, the obtained detection function and the direct fetal ECG as the reference signal. Fetal QRS complexes are marked with F.

TABLE I: DETECTION PERFORMANCE (NFN+NFP) OF THE METHODS COMPARED. TS_{bc} AND TS_{wc} DENOTE TEMPLATE SUBTRACTION IN THE BEST AND THE WORST SIGNAL CHANNELS, RESPECTIVELY; NFQRS NUMBER OF FETAL QRS COMPLEXES IN THE SIGNAL

Signal:N _{fgrs}	Methods			
	STF	ICA	TS _{bc}	TS _{wc}
r01:640	1+1	25+25	3+1	10+4
r04:628	17+13	584+388	12+5	97+89
r07:623	3+1	437+467	3+0	75+75
r08:647	1+1	8+10	12+10	30+24
r10:624	3+3	236+217	5+4	124+119
all:3162	25+19	1290+1107	35+20	336+311

Since the TS method extracts the fetal ECG in the individual signal channels, for this method we have presented in Table I the results obtained in the best TS_{bc} and the worst channel TS_{wc}, respectively.

We can notice that for 3 signals the ICA method has failed. The method of template subtraction produced rather good results in most cases, with the numbers of the detection errors depending mostly on the quality of the individual signal channels. In 3 cases STF appeared more effective than this method (when applied in the best signal channels). It should be emphasized that after the initial phase of STF weights estimation, this filter action is extraordinarily simple and fast, similar to the usual FIR filtering. Nevertheless, it allows to achieve two important goals of maternal ECG suppression and fetal ECG enhancement. After initialization it can be applied very easily which makes it attractive for the purpose of application in real instrumentation for online monitoring of the fetal heart rate.

IV. CONCLUSION

Application of spatio-temporal FIR filter to maternal abdominal bioelectric signals processing allows to achieve two important goals simultaneously: suppression of

the maternal ECG and enhancement of the fetal QRS complexes for the purpose of their detection. The method is attractive because of its simplicity, low computational costs and high detection performance. Compared to independent component analysis, it appeared effective even in cases when ICA failed. Compared to the method of template subtraction it also appeared more advantageous. Moreover, it was presented that when we know the desired component shape, STF allows for its successful detection even in places where it is completely hidden by higher level of noise.

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