Biocybernetics and Biomedical Engineering
2008, Volume 28, Number 1, pp. 75–93

Combined Application of Independent Component Analysis and Projective Filtering to Fetal ECG Extraction

MARIAN KOTAS*

Institute of Electronics, Division of Biomedical Electronics,
Silesian University of Technology, Gliwice, Poland

The maternal abdominal signals contain a few components: the dominant maternal ECG, various types of noise and the signal of the primary interest — the fetal ECG. In order to obtain the fetal ECG, the maternal signal should first be suppressed. In the paper, we propose a combined application of the independent component analysis and projective filtering of the time-aligned beats to solve the problem of the fetal ECG extraction from multichannel abdominal signals, when the number of the channels is low. The independent component analysis performs spatial decomposition of the signals. It often leads to a successful separation of the maternal and the fetal ECG. When the separation is not complete, projective filtering can be applied to enhance the partially separated maternal ECG. Then the maternal ECG contained in the respective channels can be reconstructed and subtracted from the original composite signals. This operation leads to the extraction of the fetal ECG in the respective channels. The signal can still be enhanced by the second application of the independent component analysis. The developed system operation is illustrated, and the results of its application are compared to the results achievable by application of the independent component analysis.

Keywords: independent component analysis, projective filtering, fetal ECG

1. Introduction

The first demonstration of the fetal electrocardiogram (FECG) was carried out in 1906 by Cremer [1]. However, this achievement was ignored for more than two decades. Later many experiments with the invasive techniques of the FECG recording were performed. In the seventies, the first attempts with the noninvasive techniques were made. They were based on the signals recorded from the maternal abdominal wall.

---

* Correspondence to: Marian Kotas, Institute of Electronics, Division of Biomedical Electronics, Silesian University of Technology, Akademicka 16, 44-100 Gliwice, Poland, e-mail: mkotas@polsl.pl

However, such signals contain not only the fetal ECG, but primarily the maternal electrocardiogram (MECG) and various types of contaminations. Since the maternal signal is, in most cases, of a much higher level than the fetal one, the first operation which should be performed is the maternal electrocardiogram (MECG) suppression. About 20–30 years ago the problem was a real challenge. With the decades of experiments many methods of the maternal ECG suppression were developed.

Two most important approaches to cope the problem can be distinguished. The first approach is based on the analysis of the single-channel signals. It involves the approximate repeatability of the ECG to achieve the goal of separation. Construction of the MECG beat template and subtraction of this template from the analyzed signal in the places where individual beats occur is a simple, yet effective solution of the problem [2]. The second approach is based on the analysis of multichannel signals. In [3] 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 [4] a weighted addition of four signals from the abdominal wall 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 [5]. Application of not only the second (as in [5]), but also of higher order statistical conditions of independence allowed to achieve a great progress in the accomplishment of the separation task [6]. The method applied is called the independent component analysis (ICA). Since the work [6] appeared, many different algorithms of the independent component analysis have been applied to the problem of FECG extraction [7–9]. All the mentioned techniques involve redundancy of the multichannel ECG recordings. Therefore, in most cases, at least three or four signals are required to achieve the successful separation of the maternal and the fetal ECG.

Although most of the aforementioned articles focus on the problem of maternal ECG suppression, the effective accomplishment of this task does not always lead to the successful extraction of the fetal ECG. Sometimes the FECG amplitude is so low that after cancellation of the maternal ECG this component remains hidden by electromyographic (EMG) noise. The particularly extreme fall in the FECG level can be observed between 24th and 36th week of pregnancy when the vernix layer causing the signal attenuation is formed around the uterus [12]. Although it was reported [10] that the FECG extraction can be accomplished even in signals of extremely low signal-to-noise ratio (SNR), in fact, it cannot be guaranteed. The optimistic conclusions presented in [10] were derived on the basis of a simulation experiment which was not representative to real-life problems. The most controversial was simulating the EMG component in the respective channels as the same signal of only different amplitude. Such simulation allowed an almost complete cancellation of this component, irrespective of its level, which resulted in producing the FECG of high quality. Usually the SNR ratio of the extracted FECG is rather low. It allows for an automatic detection of the QRS complexes but only exceptionally for the detection of the P and the T waves (as it was reported in [11]). To identify these low amplitude waves, synchronized averaging [13] or synchronized adaptive filtering [14] should first be applied.

The independent component analysis, which allows the FECG extraction, can also be applied to the analysis of the magnetocardiographic recordings [15–17]. Fetal magnetocardiography (fMCG) is almost unaffected by the vernix caseosa and can be applied with high rate of successes in different gestation periods [15]. The method is effective even in cases of twin-pregnancies [16]. Unfortunately the technique is very expensive, and the MCG signals recording should be performed in magnetically shielded rooms by a highly qualified personnel [17]. These requirements limit the fMCG applications and justify further work on the noninvasive fetal electrocardiography.

With the growing number of the channels, the FECG extraction by application of the independent component analysis becomes more and more feasible, but the patient's discomfort raises. Applying a single-lead system, the discomfort is reduced, but the risk of an unrecoverable loss of information is faced if something disadvantageous happens to the signal. Applying a few leads the discomfort can be limited, and we benefit from the signal redundancy. However, when the number of the recorded channels is low, e.g. two or three, the dilemma which approach to choose is faced. On one hand, using the single-channel approach, we waste the information contained in the simultaneously recorded signals, but on the other hand, applying the multichannel approach, we undertake the risk of a failure. It is possible to try the multichannel approach and, if it fails, to apply the single-channel one to the respective signals recorded.

In this work we propose a different solution of the dilemma. A combination of the multichannel and the single-channel approach makes possible utilizing both types of the ECG signals redundancy. The independent component analysis is applied to perform the spatial separation of the abdominal signals components. A single-channel approach based on projective filtering of the time-aligned ECG beats [18] is employed to improve the results of the separation.

The rest of the paper is organized as follows: Section 2 describes the method of the independent component analysis, the method of projective filtering, and the developed system for the fetal ECG extraction, Section 3 presents the system operation including a comparison with the results obtained by ICA alone. Section 4 is devoted to the final conclusions.

2. Methods

A. *Blind source separation model, applied to multichannel maternal abdominal ECG signals*

The model 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, and by the fetal heart

$$
\begin{array}{llll}
y_1(n) = & a_{1,1}s_1(n) + \ldots & +a_{1,K}s_K(n) + d_1(n) \\
\ldots & \ldots & \ldots \\
y_K(n) = & a_{K,1}s_1(n) + \ldots & +a_{K,K}s_K(n) + d_K(n)
\end{array}
\tag{1}
$$

where $y_i(n)$ is the ith measured signal, $s_j(n)$ — the jth source signal, $d_i(n)$ — independent noise, $a_{i,j}$ — coefficients of the source signals linear transform.

In this model for simplicity the same number of measured and source signals is assumed. Equation (1) can be expressed in the matrix notation as

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

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, $\mathbf{d}^{(n)}$ — the vector of independent noise, $\mathbf{A}$ — the transforming (mixing) matrix.

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

$$\hat{\mathbf{s}}^{(n)} = \mathbf{A}^{-1}\mathbf{y}^{(n)} = \mathbf{A}^{-1}\mathbf{A}\,\mathbf{s}^{(n)} + \mathbf{A}^{-1}\mathbf{d}^{(n)} = \mathbf{s}^{(n)} + \mathbf{d}'^{(n)}\,. \tag{3}$$

Since A is unknown in advance a calculation of the separating matrix should be performed in any other way, e.g. by exploiting the conditions of the statistical signals independence. This is the goal of the blind source separation methods.

In one approach to the separating matrix estimation, diagonalization of the covariance matrix is performed. It results in the orthogonal estimates of the source signals. The technique is called the Principal Component Analysis [19]. But independence cannot be reduced to simple orthogonality conditions. It can easily be seen from the fact that there are only $K(K–1)/2$ of such conditions (off diagonal elements of the covariance matrix, which should be equal to zero) and K^2 of unknown parameters in the estimated **A** matrix.

Although the second order statistical information doesn't allow to solve the problem of the **A** matrix estimation, it is used in some of the developed algorithms of the independent component analysis [7, 20], which can be treated as a fine tuning of the PCA solution. The algorithm applied in this work is called JADE, which stands for joint approximate diagonalization of eigenmatrices. Apart from the conditions of orthogonality, the algorithm utilizes the higher order statistics, the fourth order cumulants, as the statistical conditions of the source signals independence. Details of the algorithm can be found in [7]. Here we will only mention an important indeterminacy of the model (1,2) and its ICA solution: the order of the source signals is immaterial because it can be compensated for by permutation of the **A** matrix columns. Therefore, after application of ICA to multichannel ECG signals, the analysis of the obtained estimates must be performed in the search for the source signals of interest (the maternal ECG, the fetal ECG and so on). Applying JADE, estimate $\hat{\mathbf{A}}$ of the mixing matrix, and its inverse separating matrix $\hat{\mathbf{A}}^{(-1)}$ are obtained. Then the source signals are estimated according to (3) with the unknown separating matrix $\mathbf{A}^{-1}$ replaced by its estimate $\hat{\mathbf{A}}^{(-1)}$.

The measured signals vector can be reconstructed by remixing the obtained source signals estimates

$$\mathbf{y}^{(n)} = \hat{\mathbf{A}} \cdot \hat{\mathbf{s}}^{(n)} \tag{4}$$

where each column of $\hat{\mathbf{A}} = [\hat{\mathbf{a}}_k]_{k=1}^{k=K}$ corresponds to one of the source signals estimates and contains the weights $\hat{a}_{i,k}$ by which the kth source signal is multiplied before adding to the ith channel signal, according to the equation

$$y_i(n) = \sum_{k=1}^{k=K} \hat{a}_{i,k} \hat{s}_k(n) \tag{5}$$

which is equivalent to (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 [6, 8] the separation of source subspaces rather than source signals is considered. Estimates of the source signals 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, then the operation can be defined as

$$y_{\Phi,i}(n) = \sum_{k \in \Phi} \hat{a}_{i,k} \hat{s}_k(n) \tag{6}$$

where $y_{\Phi,\mathrm{i}}(n)$ denotes the ith measured signal reconstructed on the basis of the chosen source subspace.

B. Projective filtering of the time-aligned ECG beats

In the application considered, a preprocessing step of the operation makes use of the following techniques: linear filtering for the low frequency noise suppression, QRS complex detection [21], cross-correlation function based synchronization of the detected complexes. This operation produces a set of fiducial marks $\{r_k \mid k = 1, 2, \ldots, K+1\}$ corresponding to the same position within the respective detected QRS complexes.

Once the fiducial marks are established, projective filtering can be applied [18]. 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:

$$\mathbf{x}^{(n)} = [x(n), x(n+\tau), \ldots, x(n+(m-1)\tau)]^T \tag{7}$$

where $x(n)$ is the processed one-dimensional signal, τ is the time lag (following [18] $\tau = 1$ is applied), m is the embedding dimension.

2. The learning phase of the method consists in application of the principal component analysis (PCA [19]) to the construction of the local signal subspaces (LSS) for each position j within a beat. Here the term local refers to the position within the beat, but it is assumed that such a position determines the points localization in the embedding space as well.

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 projective filtering operates in a blockwise manner, on signal segments of the assumed length, which should be sufficiently high to enable an effective accomplishment of the learning phase. Parameter K is equal to the number of ECG beats in a segment. Such an approach was applied in this study. An alternative one is based on specifying the required number K. In both cases, however, when longer ECG records are to be processed, they should be divided into successive segments (possibly overlapping), according to the chosen approach. The analysis of a single ECG segment is performed in the following way.

We assume that each beat begins b samples before its fiducial mark and ends $b+1$ samples before the fiducial mark of the next beat. In order to facilitate construction of local signal subspaces (LSS), we store the beats in auxiliary matrix **T**. Each beat occupies one column of $\mathbf{T} = [\mathbf{t}_k]_{k=1}^{k=K}$. The number of rows (which will be denoted as I) depends on the length $RR_{\max}$ of the longest beat. It must be large enough to allow construction of a signal subspace for $j = RR_{\max}$. Thus, we set $I = RR_{\max} + (m-1)$, and all the beats in **T** are extended to this length. A few extension methods have been considered in the literature [22]; we apply the method of the zero order extension that extends a beat by repeating its last sample.

Time-alignment of the beats enables an easy determination of LSS corresponding to the respective positions within a beat. To this end, for each j ($1 \leq j \leq \mathrm{RR}_{\max}$) we select a submatrix of **T**

$$\mathbf{T}^{(j)} = [\mathbf{t}_k^{(j)}]_{k=1}^{k=K} = [t_{i,k}^{(j)}]_{i,k=1}^{i=m,k=K}, \quad \text{where } t_{i,k}^{(j)} = t_{i-1+j,k} \tag{8}$$

containing the vectors $\mathbf{t}_k^{(j)}$ that correspond to the synchronized trajectory points. We form a local neighborhood $\Gamma^{(j)}$ by rejecting the assumed fraction c_ρ of the most distant points.

After determination of the local neighborhood, local mean $\overline{\mathbf{t}}_k^{(j)}$ is computed and the covariance matrix of the deviations from the mean is defined as

$$\mathbf{C}^{(j)} = \frac{1}{\left|\Gamma^{(j)}\right|} \sum_{k \in \Gamma^{(j)}} \left(\mathbf{t}_k^{(j)} - \overline{\mathbf{t}}^{(j)}\right)\left(\mathbf{t}_k^{(j)} - \overline{\mathbf{t}}^{(j)}\right)^T . \tag{9}$$

A local signal subspace corresponding to the jth neighborhood is calculated by eigendecomposition of the covariance matrix

$$\mathbf{C}^{(j)} = \mathbf{E}^{(j)}\mathbf{\Delta}^{(j)}\mathbf{E}^{(j)T}, \tag{10}$$

where $\mathbf{E}^{(j)} = [\,\mathbf{e}_1^{(j)}, \dots, \mathbf{e}_\mathrm{m}^{(j)}\,]$, $\Delta^{(j)} = \mathrm{diag}\,(\,\delta_1^{(j)}, \dots, \delta_\mathrm{m}^{(j)})$, $|\Gamma^{(j)}|$ denotes the jth neighborhood cardinality.

Within the local neighborhood the eigenvectors $\mathbf{e}_i$ are the principal axes [19] (principal components directions) of the deviations from the mean. The corresponding eigenvalues δ_i are equal to the total energy of the deviations in these directions. The signal subspaces are composed of the first q ($q < m$) principal axes

$$\mathbf{E}_q^{(j)} = [\mathbf{e}_1^{(j)}, \dots, \mathbf{e}_q^{(j)}]. \tag{11}$$

The processing phase consists of the following steps.
Determination of position j within a beat, the point under correction belongs to

$$\underset{r_k - b \le n < r_{k+1} - b}{\forall} \quad j(n) = \begin{cases} n - r_k + b + 1, & n - r_k + b < RR_\mathrm{max} \\ RR_\mathrm{max}, & \text{elsewhere} \end{cases} \tag{12}$$

Projecting the processed point into the corresponding signal subspace

$$\mathbf{x}'^{(n)} = \bar{\mathbf{t}}^{(j(n))} + \mathbf{E}_q^{(j(n))}\mathbf{E}_q^{(j(n))T}(\mathbf{x}^{(n)} - \bar{\mathbf{t}}^{(j(n))}) \tag{13}$$

The nth sample of the processed signal occurs in m trajectory points, as the lth entry $x_l^{(n-l+1)}$ of vector $\mathbf{x}^{(n-l+1)}$. Averaging the results of the respective points projection according to the formula

$$x'(n) = \tfrac{1}{m}\sum_{l=1}^{m} x'^{(n-l+1)}_l \tag{14}$$

ends the processing phase of projective filtering. A more detailed description of the method can be found in [18].

C. *A combined application of the independent component analysis and the projective filtering to fetal ECG extraction*

The operation is performed according to the block diagram in Fig.1. Locating the electrodes on the maternal abdomen, the signals which contain the maternal ECG, the wide-band electromyographic (EMG) noise, the low frequency baseline wandering, the 50 Hz powerline interference and the signal of the primary interest — the fetal ECG are obtained. To simplify the problem we assume that the input signal is measured using the electronic amplifiers with a high common mode rejection ratio to eliminate the powerline interference. Still a variety of contaminating signals are to be suppressed. To attenuate the low frequency contaminations, the digital high-pass filters can be applied in block B1.

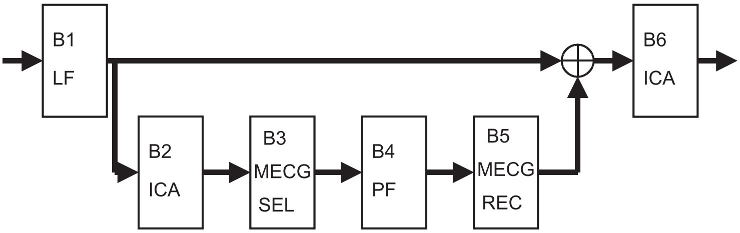

Fig. 1. Block diagram of the system for the fetal ECG extraction: (B1) linear filters, (B2) source signals estimation by application of ICA, (B3) selection of the maternal source signals, (B4) projective filtering of the maternal source signals, (B5) reconstruction of the MECG contained in the respective channels, (B6) application of ICA for fetal ECG enhancement

The output of the filters undergoes the independent component analysis in block B2. The estimated source signals are visually inspected in B3, and the signals generated by the maternal heart are selected. Each of the selected maternal ECG source signals undergoes the projective filtering in B3. The aim of the operation is to enhance the maternal ECG and suppress the other components, first and foremost the fetal ECG, if ICA fails to separate the maternal and the fetal source signals. After this operation, on the basis of the enhanced maternal ECG source subspace, reconstruction of the MECG contained in the respective measured signals is performed (in block B5, according to (6) with the maternal source signals enhanced by the projective filtering). Subtraction of the reconstructed MECG from the original signals leads to the maternal ECG suppression in the respective measured signals, and extraction of the fetal ECG. Even if some residua of the MECG component still remain in the measured signals, the lower number of source signals makes possible a successful separation by application of ICA in B6. This stage is aimed to enhance the fetal ECG by the operation of spatial filtering.

Both JADE [7] and projective filtering of the time-aligned ECG beats [18] operate in a blockwise manner, on the assumed length segments of the signals. First, after high-pass filtering the whole signal segment is analyzed by Jade, and then the projective filtering is performed. Finally, ICA is applied again in the block B6. When longer records are analyzed, they must be divided into signal segments of the proper length.

3. Results and Discussion

The proposed system for the fetal ECG extraction requires a careful adjustment of parameters that assure its high performance. Among the most important parameters are these of the applied projective filter: index b pointing to where the beats stored in the matrix **T** begin, fraction c_p of the points rejected while local neighborhoods are being constructed, embedding dimension m, and dimension q of local signal subspaces. It is also important to choose a proper length of the analyzed signal segments, and the cutoff frequency of the high-pass filter in block B1.

Because of the extremely high level of the low frequency noise in the abdominal ECG signals, we decided to use a high-pass filter with the cut-off frequency of 5 Hz in the block B1 (according to [23, 24] even a higher value of this parameter could be applied to prepare the fetal ECG for the purpose of QRS detection). Parameter b in the block B4 of maternal ECG enhancement was set to 120 and with the sampling frequency of the analyzed signals equal to 400 Hz, this value corresponds to the interval of 300 ms. For c_p we applied the value of 0.1 as in [18]. In [18] the length of the processed signal segment was equal to 80 s. Such value is advantageous, but it is not crucial, and the proposed system works effectively for a wide range of values of this parameter. In the experiments presented in this study we analyzed the signal segments of about 3 minutes. After many experiments embedding dimension m=60 was chosen, corresponding to the interval of 150 ms.

Dimension q of local signal subspaces is particularly important. With the growth of q the morphological variability of the processed ECG is reconstructed more precisely, but suppression of the undesired components is less effective. It is advantageous to use higher dimensions in highly variable parts of ECG beats, and lower in more repeatable sections. The projective filtering of the time-aligned beats offers such possibilities. After many experiments the dimensions calculated as in Fig. 2 were applied in the block B4. The figure presents a plot of q as a function of the position within a beat. The width of the non-zero part of the function is equal to the embedding dimension m. Thus the first signal subspace with non-zero dimension corresponds to the embedding space vectors that overlap the left side of the QRS complex, and the last one to the vectors that overlap the right side of the complex. Application of such dimensions of local signal subspaces allows enhancing the maternal source signals with effective suppression of the FECG.

The developed system operation will be illustrated with the results obtained for the signals of four patients. The signals were recorded with the use of the four abdominal leads proposed in [4]. Each abdominal signal was the potential difference between one of the measurement electrodes (located on the maternal abdomen at the height of the umbilicus) and the reference electrode (located above the symphysis pubis). The respective signals were amplified (with a gain of 2000) and band-pass filtered (with the pass-band of 0.05–120 Hz). Then the signals were simultaneously sampled with the sampling rate of 400 Hz. During recording the investigated pregnant women were in a supine position. The method described in [4] requires four abdominal signals to achieve the successful suppression of the maternal ECG, and this number of signals was recorded. The experiments performed showed, however, that the method proposed in this paper was able to suppress the maternal ECG in all cases when only three signals were analyzed. To show this ability of the method, in the experiments presented, in each of the four cases, we used the first three of the recorded four abdominal signals.

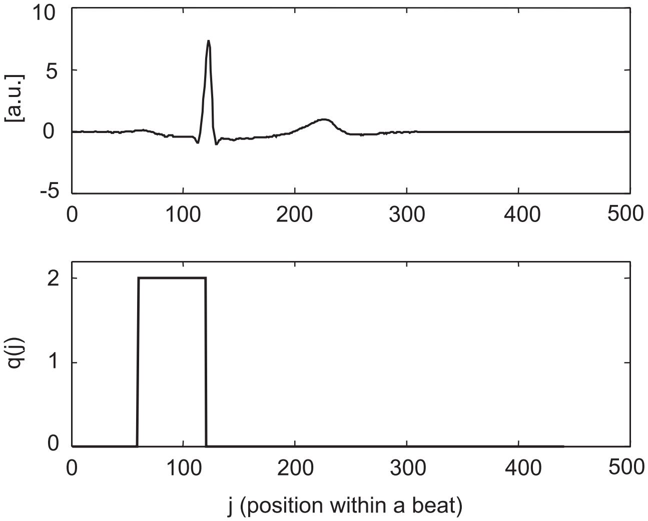

Fig. 2. The dimensions of local signal subspaces of the projective filter that assure precise reconstruction of the maternal ECG contained in the source signals estimates (with effective suppression of the undesired components). The upper picture presents the average maternal ECG beat extended to the length $I = RR_{max} + \mathrm{m} - 1$ (see description of the method); the lower one the dimensions corresponding to the respective positions within the beat ($j = 1,2,\ldots,RR_{max}$). The embedding dimension $m = 60$ was applied. Since the source signals estimates are rescaled to be of unit variance, their amplitude is immaterial; therefore the upper signal is presented in arbitrary units

Figure 3 presents the first such a three channel abdominal signal, obtained after a high-pass filtering in B1. The signal is of a high quality. Each channel contains a dominant maternal and also a well visible fetal ECG. Application of ICA in B2 allowed to achieve a successful extraction of the fetal ECG (presented in the lowest subplot of Fig. 4). Although separation of the maternal and the fetal 'sources' was not complete (the estimate presented in the middle subplot contains both components), the extracted fetal signal contains clearly visible QRS complexes. The upper two signals are selected in the block B3. At this moment we cannot claim that these signals compose the maternal ECG source subspace only, because of the presence of the fetal ECG. However, application of the projective filtering allowed to suppress this component and the enhanced estimates presented in Fig. 5 composed this subspace. The estimates can be used, according to (6) for the reconstruction of the maternal ECG contained in the original measured signals (compare Fig. 6 to Fig. 3). Subtraction of the respective reconstructed signals (Fig. 6) from their original equivalents

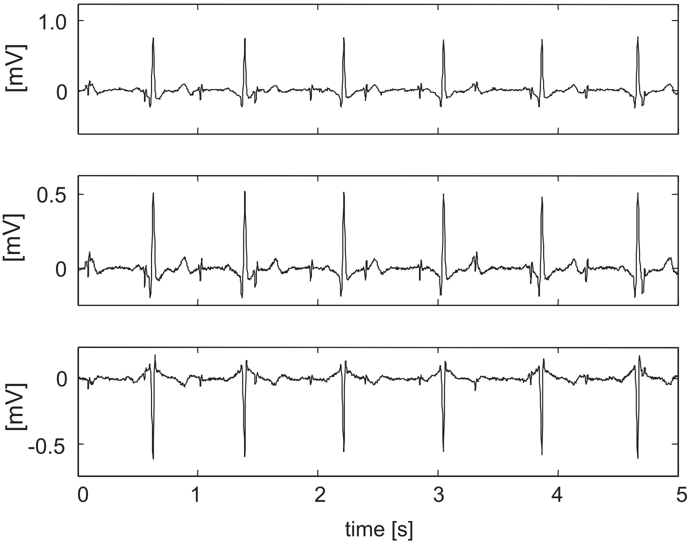

Fig. 3. The maternal abdominal signals recorded by application of the first three abdominal leads of the configuration proposed in [4]. The presented signals, containing the maternal ECG, the fetal ECG and the noise, were previously high-pass filtered in the block B1

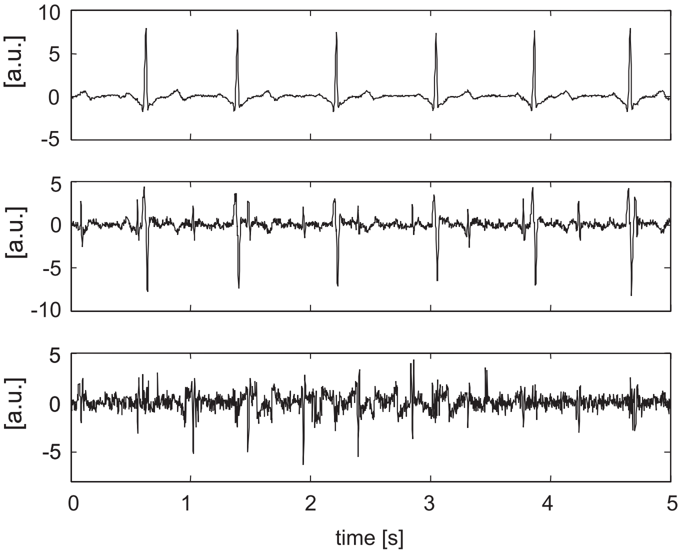

Fig. 4. The source signals estimates obtained after the ICA decomposition of the signals from Fig. 3. The upper two signals, dominated by the maternal ECG, compose the maternal source subspace (slightly contaminated, however, by the fetal ECG). The lowest signal contains the extracted fetal ECG. The signals are presented in arbitrary units

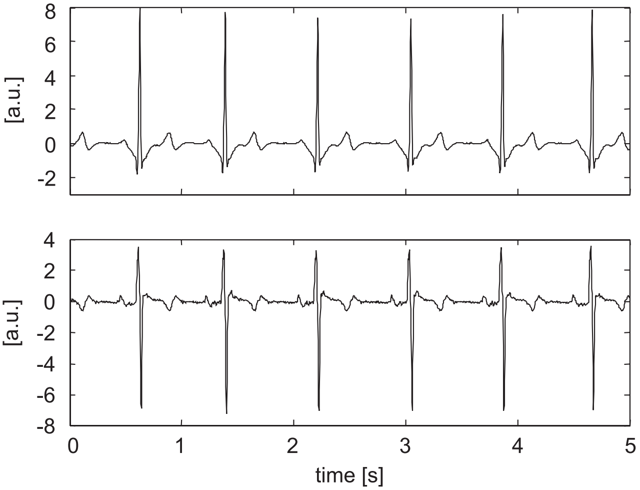

Fig. 5. The source signals composing the maternal source subspace (see Fig. 4), enhanced by application of the projective filtering. The signals are presented in arbitrary units

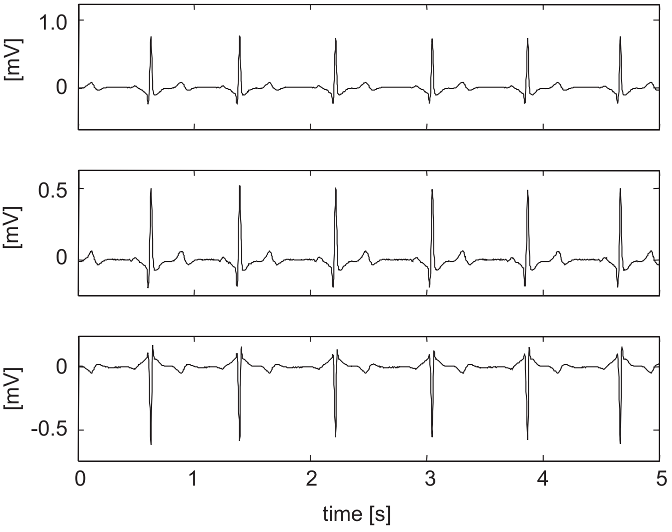

Fig. 6. The maternal ECGs contained in the respective channels, reconstructed by reprojecting the enhanced maternal source signals (see Fig. 5) according to (6)

(Fig. 3) allows to extract the fetal ECG contained in the respective channels (Fig. 7). The quality of these signals is very high (as for the fetal ECG), but application of ICA can help raise it as a result of the spatial filtering (Fig. 8). In Fig. 9 the obtained signal is compared with the signal extracted by application of ICA. The improvement of the extracted signal quality is out of the question. However, as it was investigated in [25] the results of maternal and fetal source signals separation depend on a few

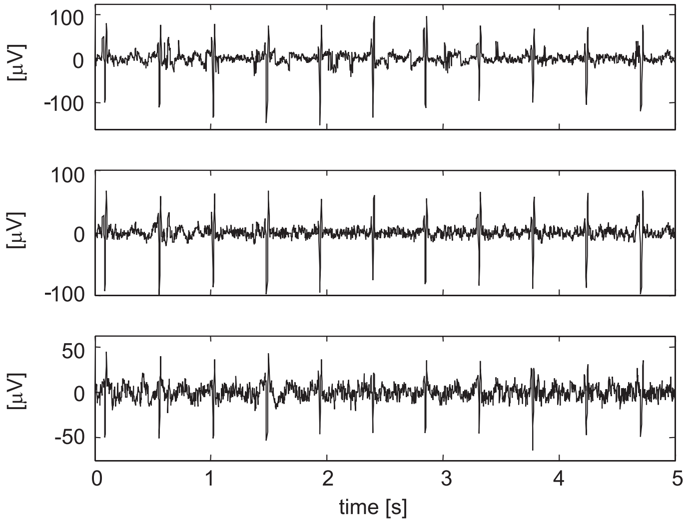

Fig. 7. The fetal ECG signals extracted by subtraction of the reconstructed maternal ECGs (presented in Fig. 6) from the original signals (presented in Fig. 3)

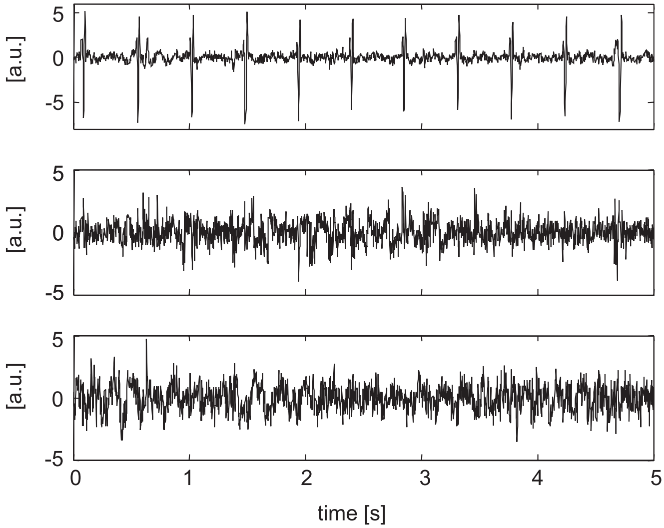

Fig. 8. Results of the ICA method application to the analysis of the extracted fetal ECGs (see Fig. 7). The operation performed in the block B6 (see Fig. 1) allowed to obtain the enhanced fetal ECG (presented in the uppermost subplot). The signals are presented in arbitrary units

conditions. The primary condition is the required number of the measured signals (according to the presented model as many measured as the source signals). With the higher number of channels the method is very effective. But very often even three channels are enough to achieve a quality extraction of the fetal ECG. The second example illustrates such a situation. The three channel signal presented in Fig. 10 contains the maternal ECG of different level, and the fetal ECG mostly in the middle signal. This signal is of a relatively unique type, because it contains the fetal and the maternal components of a comparable level. In this case application of ICA allowed to extract a high level, good quality fetal ECG. Application of the proposed system

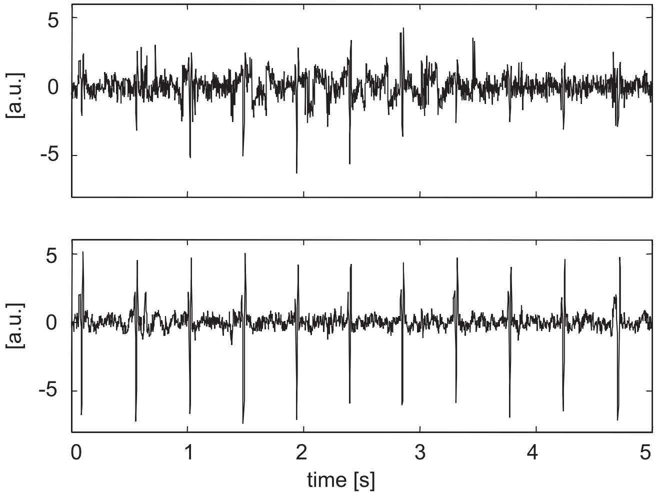

Fig. 9. A comparison of the fetal ECG from Fig. 8, obtained by application of the developed system (the lower picture) with the signal from Fig. 4, obtained by application of ICA only (the upper picture). The signals are presented in arbitrary units

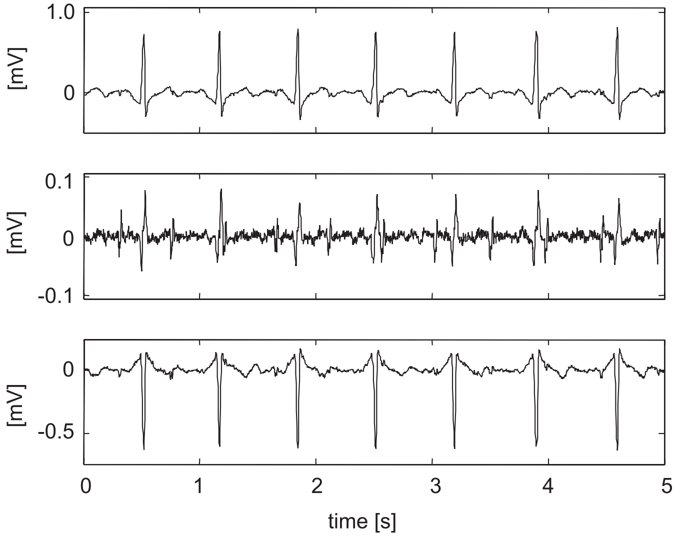

Fig. 10. The analyzed maternal abdominal signals — the second example (the description of the signals as in Fig. 3)

did not help raise the quality of the signal extracted (see Fig. 11). One of the factors that caused such a situation was the concentration of the fetal ECG in one channel. Application of the spatial filtering (ICA) could not cause the signal enhancement in such conditions. The next example, presented in Fig. 12 and Fig. 13, shows the case when ICA failed to separate the fetal ECG successfully. Although the FECG

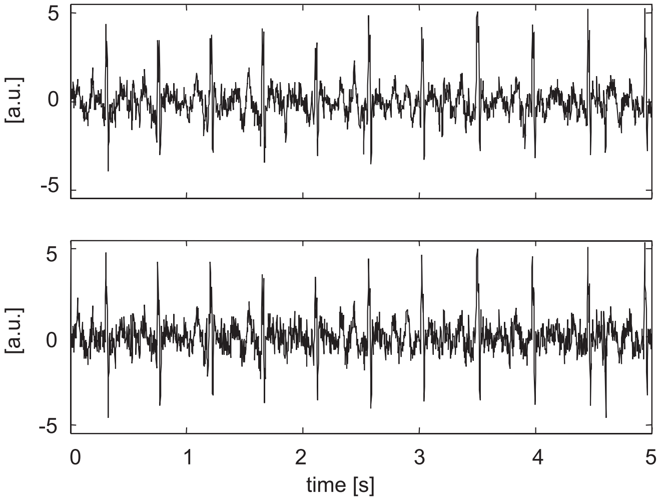

Fig. 11. A comparison of the fetal ECG obtained by application of the developed system (the lower picture) with the signal obtained by application of ICA only, for the signals from Fig. 10. The signals are presented in arbitrary units

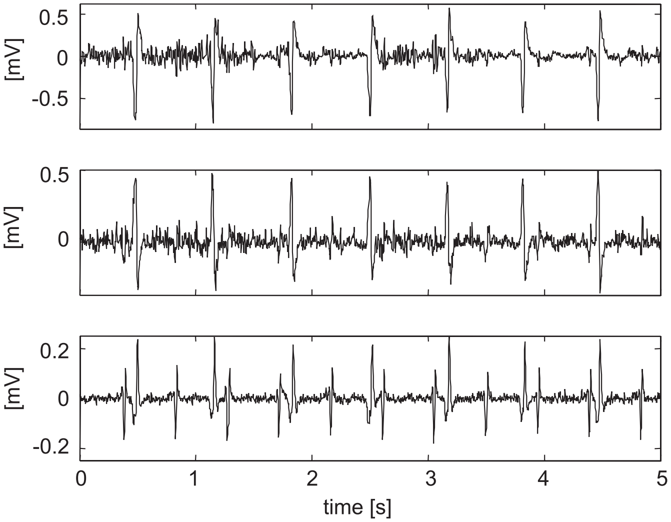

Fig. 12. The analyzed maternal abdominal signals — the third example (the description of the signals as in Fig. 3)

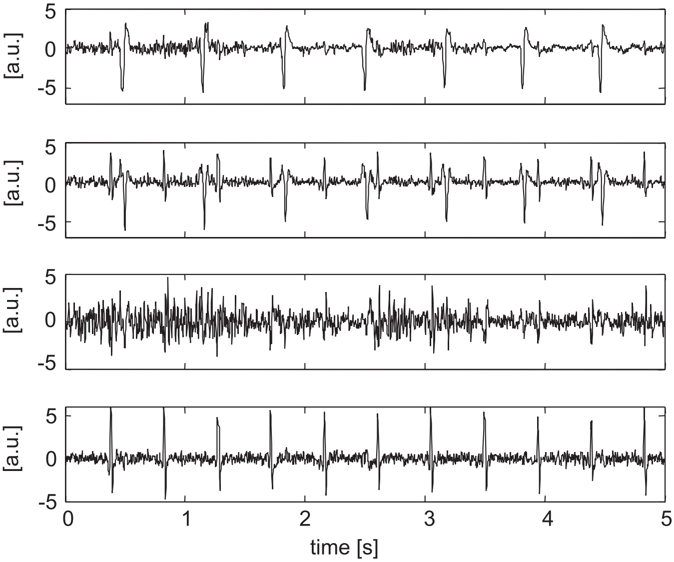

Fig. 13. The results of the ICA decomposition (the upper three subplots) of the signals from Fig. 12, and the FECG extracted by the proposed system (the lowest subplot). The signals are presented in arbitrary units

amplitude in the third measured signal was very high, after the decomposition the obtained fetal component was embedded in the wide-band EMG noise. In this case application of the proposed system produced a high quality FECG.

The second and the third example span the range of the results which can be achieved by ICA when applied to the analysis of three channel signals containing a distinct FECG component. In all these cases we could have reported a success of ICA, because the fetal ECG was discernible in the results obtained. However, comparison with the results achieved by the developed system prevented us from such an optimism. The further analysis of the FECG signals obtained by ICA in the first and the third example would be very complicated. Application of the proposed system produced good results in all the cases presented. Thus, the further stages of signal processing, such as the QRS detection and the fetal heart rate determination, would be much easier if the system were employed.

The last example (Fig. 14 and Fig. 15) presents the case of a rather low FECG level. The component, embedded in the electromyographic noise, was practically invisible. In this case ICA failed completely, but the proposed system managed to produce a discernible fetal ECG. Although the analysis of such a noisy signal is complicated, nevertheless, it is possible. However, we cannot always guarantee the successful analysis of the FECG. Sometimes even effective suppression of the maternal ECG does not lead to a successful extraction this signal, because it remains hidden by a higher level of noise.

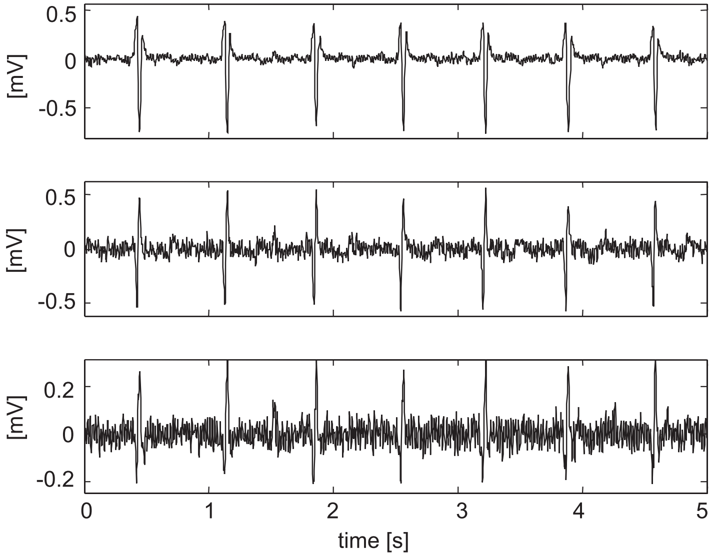

Fig. 14. The analyzed maternal abdominal signals — the fourth example (the description of the signals as in Fig. 3). The signals are characterized by a low level of the fetal ECG and a higher level of the electromyographic noise

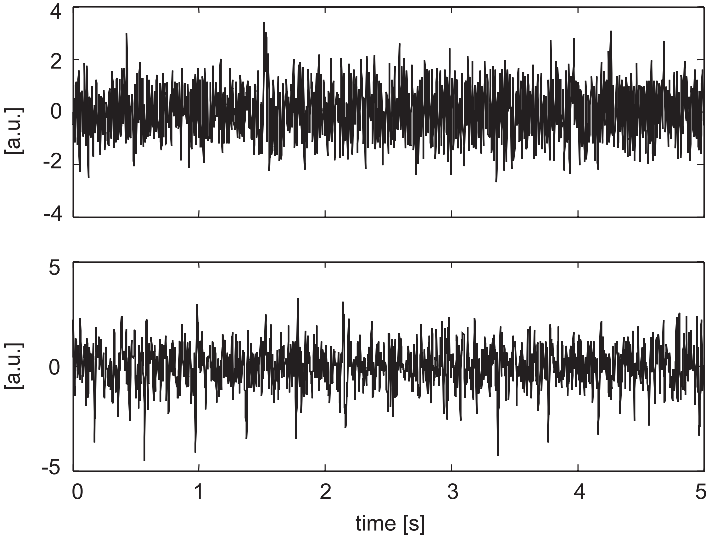

Fig. 15. A comparison of the fetal ECG obtained by application of the developed system (the lower picture) with the signal obtained by application of ICA only, for the signals from Fig. 14. Only a combined application of ICA and the projective filtering allowed to extract the discernible fetal ECG. The signals are presented in arbitrary units

4. Conclusions

Extraction of the fetal electrocardiogram from multichannel signals, when the number of channels is low, is a dilemma. Either the single-channel approach, utilizing the ECG signals repeatability, or the multichannel one, utilizing the spatial redundancy of the signal can be applied. It is not guaranteed which approach will produce better results in cases of different analyzed signals. The developed system combining the strength of the independent component analysis and projective filtering of the time-aligned beats appears to address this problem successfully. It allows to exploit both types of the ECG signals redundancy. As a result, it allows to extract the FECG effectively in cases when ICA alone fails or gives poor results. Extraction of the signal of the best possible quality is the first condition which should be satisfied to come up with an effective system for the fetal heart rate determination. Thus the proposed method can contribute well to the development of a useful device for prenatal diagnosis.

References

1. Jenkins H.M.L.: Technical progress in fetal electrocardiography-a review, J. Perinat. Med. 1986, 14, 365–370.
2. Nagel J.H.: Progress in fetal monitoring by improved data acquisition, IEEE Trans. Biomed. Eng. 1984, 31, 9–13.
3. Widrow B. et al.: Adaptive noise cancelling: principles and the applications, Proc. IEEE 1975, 63, 1692–1716.
4. Bergveld P., Kőlling A.J., Peuscher J.H.J.: Real-Time Fetal ECG Recording, IEEE Trans. Biomed. Eng., 1986, 33, 505–509.
5. 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. 1990, 28, 217–224.
6. De Lathauwer L., Callaertr D., De Moor B., Vandevalle J.: Fetal electrocardiogram extraction by source subspace separation, Proc. IEEE SP/ATHOS Workshop on HOS, Girona, Spain, June 1995, 134–138.
7. Cardoso J.-F., Souloumiac A.: Blind beamforming for non-Gaussian signals, Inst. Elect. Eng. Proc.-F. 140, 6, 362–370.
8. Cardoso J.-F.: Multidimensional Independent Component Analysis, Proc. ICASSP'98, vol. IV, Seattle, WA, May 1998, 1941–1944.
9. Zarcoso, Nandi A.K.: Noninvasive Fetal Electrocardiogram Extraction: Blind Separation Versus Adaptive Noise Cancellation, IEEE Trans. Biomed. Eng. 2001, 48, 12–18.
10. Najafabadi F.S., Zahedi E.: Mohd Alauddin Mohd Ali, Fetal heart rate monitoring based on independent component analysis, Computers in Biology and Medicine, 2006, 36, 241–252.
11. Mochimaru F., Fujimoto Y., IshikawaY.: The Fetal Electrocardiogram by Independent Component Analysis and Wavelets, Japanese Journal of Physiology, 2004, 54, 457–463.
12. Crowe J.A., Harrison A., Hayes-Gill B.R.: The feasibility of long term fetal heart rate monitoring in the home environment using maternal abdominal electrodes, Physiological Measurement, 1995, 16, 195–202.
13. Abboud S., Barkai G., Mashiach S., Sadeh D.: Quantification of the Fetal Electrocardiogram Using Averaging Technique., Computations in Biology & Medicine, 1990, 20, 147–155.

14. Adam D., Shavit D.: Complete foetal ECG morphology recording by synchronized adaptive filtration, Medical & Biological Engineering & Computing, 1990, 28, 287–292.
15. Comani S., Mantini D., Alleva G., Di Luzio S., Romani G.L.: Fetal magnetocardiographic mapping using independent component analysis, Physiological Measurement, 2004, 25, 1459–1472.
16. Burghoff M., Van Leeuwen P.: Separation of Fetal and Maternal Magnetocardiographic Signals in Twin Pregnancy Using Independent Component Analysis (ICA), Neurology and Clinical Neurophysiology, 2004, November 30, 39.
17. Lewis M.L.: Review of electromagnetic source investigations of the fetal heart, Medical Engineering & Physics, 2003, 25, 801–810.
18. Kotas M.: Projective Filtering of the Time-Aligned ECG Beats, IEEE Trans. Biomed. Eng. 2004, 51, 1129–1139.
19. Jollife I.T.: Principal Component Analysis, New York: Springer Verlag, 1986.
20. Hyvärinen, Oja E.: A Fast Fixed-Point Algorithm for Independent Component Analysis, Neural Computation, 1997, 9, 1483–1492.
21. Hamilton P.S., Tompkins W.J.: Quantitative investigation of QRS detection rules using the MIT/BIH arrhythmia database, IEEE Trans. Biomed. Eng. 1986, 33, 1157–1165.
22. Chou H.H., Chen Y.J., Shiau Y.C., Kuo T.S.: An Effective and Efficient Compression Algorithm for ECG Signals With Irregular Periods, IEEE Trans. Biomed. Eng. 2006, 53, 1198–1205.
23. Kotas M.: Fetal QRS Detection — Quantitative Investigation of a Class of Algorithms, Biocybernetics and Biomedical Engineering, 1996, 16, No 3–4, 133–145.
24. Kotas M.: A New Method of Fetal QRS Detection, Biocybernetics and Biomedical Engineering, 1996, 16, No 3–4, 147–163.
25. Kotas M.: Independent versus Principal Component Analysis for Fetal ECG extraction, Proc. Int. Conf. SYMBIOSIS, September 11–13, Szczyrk, Poland.