Fetal heart rate (FHR), Fetal Electrocardiogram (FECG), Independent Component Analysis (ICA), Adaptive Filtering

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DIRECT ASSESSMENT OF THE FETAL HEART RATE FROM ABDOMINAL COMPOSITE RECORDINGS

In respect to the main goal of our ongoing work for analyzing fetal electrocardiogram (FECG) signals for monitoring the health of the fetus, we investigate in this paper the possibility of extracting the fetal heart rate (FHR) directly from the abdominal composite recordings. Our proposed approach is based on a combination of Independent Component Analysis (ICA) and least mean square (LMS) adaptive filter. The FHR of the estimated FECG signal is finally compared to a reference value extracted from a FECG signal recorded by using a spiral electrode attached directly to the fetal scalp. The experimental results show that FHR can be successfully evaluated directly from the abdominal composite recordings without the need of using any external reference signal.

1. INTRODUCTION

Prenatal fetal monitoring aims to test fetal intrauterine wellbeing and to recognize, in advance, various possible pathological conditions, which may help reduce fetal and neonatal morbidity and mortality. Current techniques of fetal monitoring through pregnancy and at the onset of labor are merely based on evaluating the fetal heart rate (FHR) patterns [4], [15], [5].

Among many methods to determine the FHR, the ultrasound technique is the most common. This technique uses the Doppler shift in the ultrasound signal that results from the movement of the heart valves and the movement of the heart wall [16]. The indirect ultrasound technique has become the standard approach since early 1970s despite questions about its efficiency and outcomes associated with its use [10]. Indeed, this technique suffers from many limitations such as imprecise measurement of interval distances, picking up other fetal or maternal organs, and fetal movement effects. It also requires a trained technician/physician [11], [2].

In modern day medicine, new instrumentation techniques are being developed every day to help overcome all the above limitations and to solve problems related to monitoring equipments such as efficiency, cost, and invasiveness. In this context, a large number of studies has revealed that the analysis of the electrical activity of the fetus' heart, known as fetal electrocardiogram (FECG), may offer a new direction in fetal monitoring by revealing some hidden and potentially valuable clinical information about the fetus state, thus assuring fetus wellbeing during pregnancy period even at early stage [5], [8], [18], [17].

FECG may be recorded by using a spiral electrode applied directly to the fetal scalp. This is the direct assessment of the FECG. Although it provides high signal-to-noise ratio (SNR) and thus, ensures high measurement accuracy because it records directly the FECG, this technique is highly invasive and may be used only during the onset of labor [15].

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FECG can be recorded indirectly and non-invasively by using a number of electrodes applied directly to the maternal abdomen. However, this technique detects also the maternal ECG (MECG) which has much higher amplitude than the fetal components. In addition, indirect FECG is also distorted by other biological interference signals such as the mother electromyogram (EMG) and respiration, uterine EMG, fetal movement and skin potential. Non-biological interference sources, such as power-line coupling and thermal noise from electronic equipments corrupt the indirect recordings as well. As a result, the indirect FECG signal is hidden in a sea of electrical noise [18]. To extract the signal from the composite maternal skin electrode measurement, robust biomedical signal processing techniques must be applied.

During the last decades, there have been a large number of articles published on the subject of FECG extraction from abdominal signals to analyze heart rate and the associated variability [17], [14], [19], [20]. These methods were mainly based on subtraction of the MECG component [14], [6], adaptive filtering [2], [21], and blind source separation (BSS) [19], [3].

With many investigators throughout the world making similar observations, the cancellation of MECG, which represents the source of interference of dominating energy, from the abdominal recordings became therefore the standard process to recover the FECG signal. These techniques require recording one or more direct reference MECG signals, which is practically cumbersome. Therefore, an FECG extraction method that would require no reference signals would be of great interest [18].

In this paper, we sought to demonstrate that a technique that combines both independent component Analysis (ICA) and adaptive filtering and using only the abdominal composite signals can accurately evaluate the FHR without the need of using any reference MECG signal. Herein, the FHR is determined by calculating the number of QRS complexes detected in the estimated FECG signal and compared to the FHR estimated by the same way from a reference FECG recorded directly from the fetal scalp and used herein for the sake of evaluation of the proposed method. The block diagram of the proposed approach is illustrated in Fig. 1.

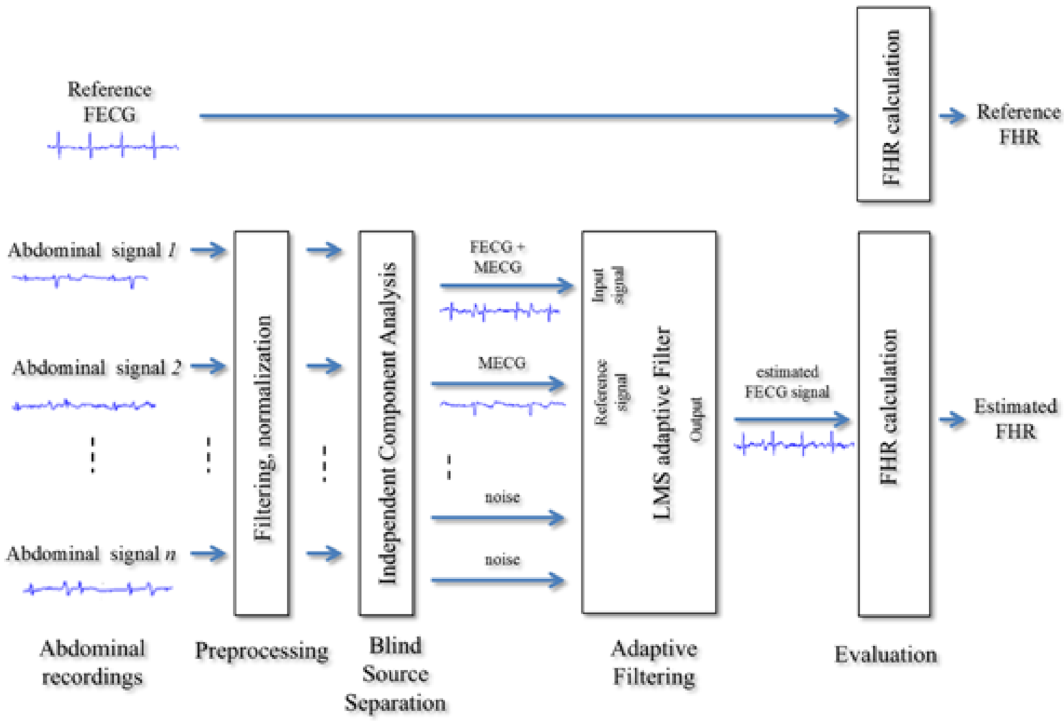

Fig. 1. Block diagram of the proposed approach.

2. MATERIALS AND METHODS

2.1. DATABASE DESCRIPTION

Our analysis in this paper is based on real clinical datasets recorded on 5 different women during established labors between 38 and 41 weeks of gestation. The measurements were made at the Department of Obstetrics at the Medical University of Silesia (Poland) [13], [9], [12]. Each dataset comprises six different signals: four composite signals acquired from maternal abdomen by using four Ag-AgCl skin electrodes placed around the navel of each pregnant woman, one direct reference ECG signal recorded simultaneously from the fetal head by using a typical spiral electrode and one fetal ECG R-wave marker determined from the reference signal (Fig. 2). The common electrode was placed on the left leg. The positioning of all the electrodes was constant during all recordings. All women consented to the participation in the study. All recordings were sampled at 1 kHz and were encoded on 16 bits [13], [9], [12]. The total duration of each recording is 5 minutes.

The problem of the FECG extraction from abdominal composite recordings can easily fit in a blind

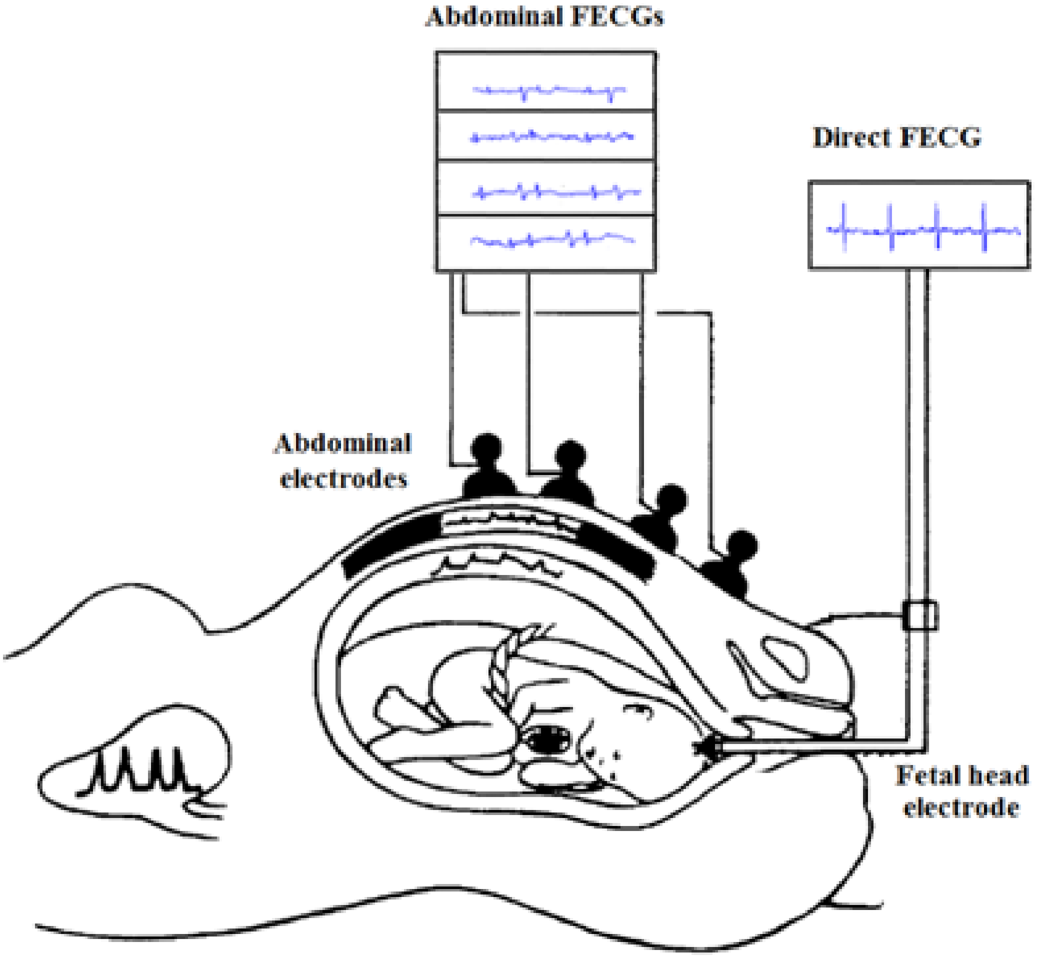

Fig. 2. Electrode configuration (original figure from [2]).

source separation (BSS) framework. ICA is a multivariable statistical analysis technique that belongs to the BSS techniques. It is used to decompose a multivariable signal into a set of mutually independent non-Gaussian components. ICA assumes that the measured signals are a combination of independent source signals. This is described mathematically by the ICA model:

$$x = A.s \tag{1}$$

where $x = [x_1, x_2, \ldots, x_M]^T$ is the observed multivariate signal, $s = [s_1, s_2, \ldots, s_N]^T$ is the original unknown multivariate source signal, M is the number of observed signals, N is the number of sources and A is the mixing matrix [7], [1]. For simplicity, we assume that the mixing matrix is linear and is a square matrix, i.e., M=N.
The aim of ICA it to return the linear unmixing matrix W in order to acquire the estimated Independent Components (ICs) y such that:

$$y = W.x \tag{2}$$

It is important to note that the signs, amplitudes, and the order of appearance of the ICs are arbitrary. In this work, the fastICA algorithm proposed in [7] was adopted due to its convergence speed.

2.2. ADAPTIVE FILTERING

An adaptive filter is a filter that self-adjusts its own parameters, based on the incoming signal so that a given performance index is optimized. Adaptive filters are very useful because they don't require any a priori knowledge of the signal and noise characteristics. In this work, the adaptive filter essentially minimizes the mean-squared error (MSE) between the primary input containing a mixture of FECG and MECG components, and the reference input containing only the MECG component, as will be explained later, in order to generate the estimated FECG signal. Fig. 3 illustrates the principle where the output of the least mean squared (LMS) filter is denoted $\overline{mecg}$ and the filter error is $\varepsilon = (fecg + mecg) - \overline{mecg}$. The filter coefficients are improved in epochs regarding the minimization of the quadratic error in equation (3) until the output signal estimates the filtered fetal ECG signal.

$$\varepsilon^2 = (fecg + mecg)^2 - 2\overline{mecg}(fecg + mecg) + \overline{mecg}^2 \tag{3}$$

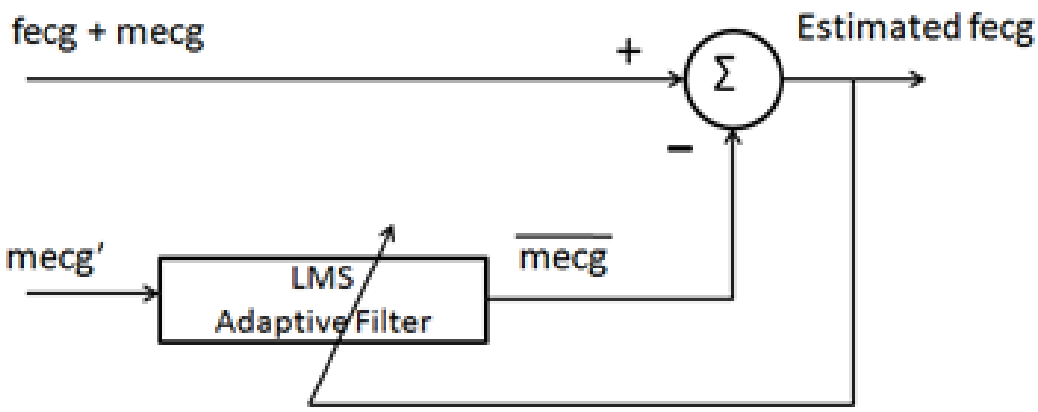

Fig. 3. Principle of the adaptive filter used.

3. RESULTS

Our approach was tested on data from 5 different women recorded during labor. Herein, the FHR was determined from sample signals of 10s each selected from the 5-minutes long recordings. Since some of the signals were highly corrupted by noise, the sample signals were selected randomly from regions representing high SNR. First, all the sample signals were filtered by a 4th order bandpass filter between 1 and 150 Hz then normalized by dividing each signal by its standard deviation. Fig. 4 shows an illustrative example of the analyzed signals with the reference FECG signal on top followed by the 4

composite abdominal signals simultaneously recorded from the mother's abdomen. After preprocessing all the signals, fastICA was applied on the matrix that consists of the 4 abdominal signals. The ICs resulting from the application of the fastICA applied to the data shown in Fig. 4 are illustrated in Fig. 5. For the sake of comparison and clarity, the reference FECG signal is illustrated also at the top of the ICs shown in Fig. 5.
From Fig. 5 we can notice that the presence of the actual FECG is evident in the second IC (IC2) and is synchronous with the reference FECG shown at the top of the same figure. Unfortunately, this IC contains also the MECG component residual. The MECG component is obtained in another IC (IC1) as indicated in Fig. 5.

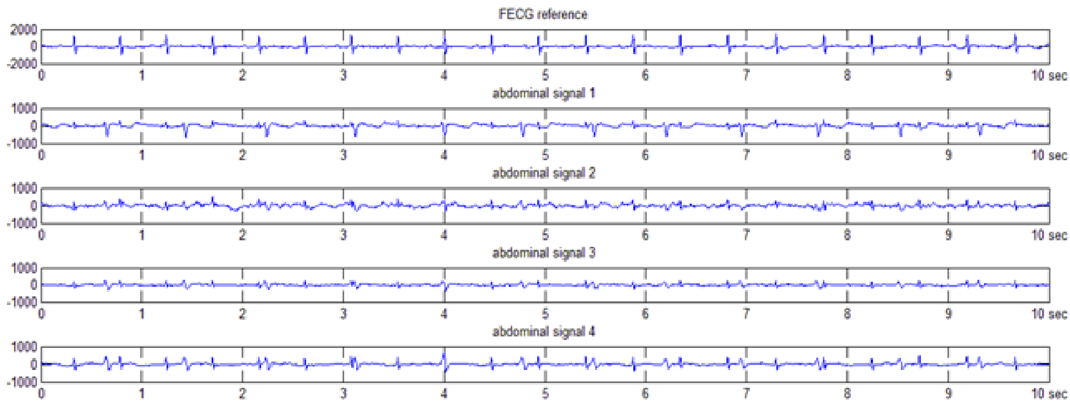

Fig. 4. Example of the recorded signals. Vertical axis represents arbitrary scale. Horizontal axis is expressed in seconds.

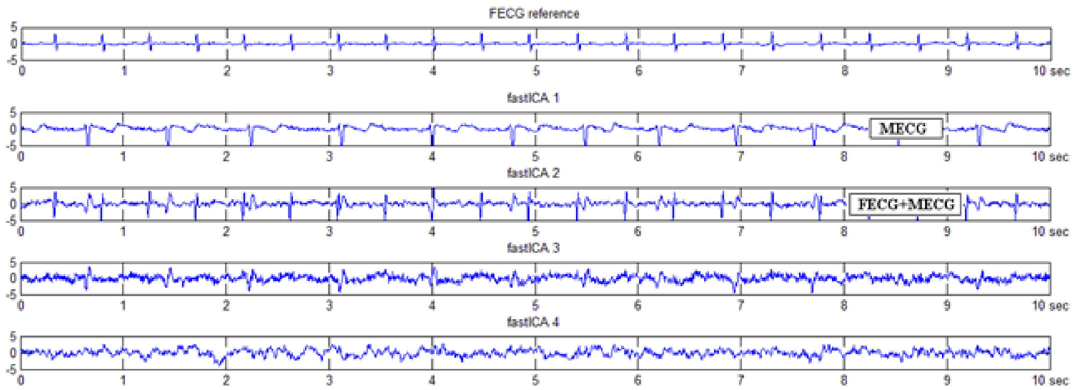

Fig. 5. Results of the fastICA algorithm applied on the same data set shown in Fig. 4. Vertical axis represents arbitrary scale. Horizontal axis is expressed in seconds.

The idea is thus to use the IC containing the MECG component as a reference in order to cancel it from the IC containing both the FECG and the MECG. Therefore, adaptive filtering was applied.
Herein, the primary input of the adaptive filter is the IC containing both the FECG and the MECG while the reference input is the IC containing only the MECG component. Thus, the output of the adaptive filter is an estimation of the actual FECG signal. Fig. 6 shows the reference FECG signal (on top) and the estimated FECG signal obtained at the output of the adaptive filter (on bottom). It is clear that the MECG is filtered out in the estimated FECG component. Finally, the FHR was determined by calculating the number of QRS detected. This was done by applying a threshold on the absolute values of the signals and computing the number of R-peaks in the two FECG waveforms over the time interval. A comparison between the FHR values, expressed in beats per minute (bpm), corresponding to both reference and estimated FECGs, denoted FHR_ref and FHR_est respectively, is illustrated in Table 1. This table shows also the error between the values calculated by using (4):

$$error = \left| \frac{FHR(estimated) - FHR(reference)}{FHR(reference)} \right| \tag{4}$$

As shown in table 1, errors as low as 0% were obtained (women1 and 4). These results show that the presented method may be used to accurately determine the FHR.

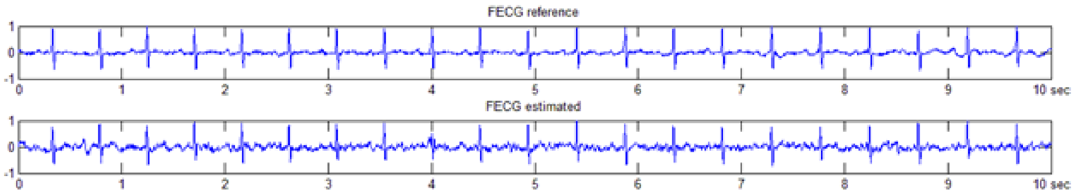

Fig. 6. Comparison between the reference (on top) and the estimated FECG (at bottom) signals. Vertical axis represents arbitrary scale. Horizontal axis is expressed in seconds.

Table 1. FHR values based on the calculation of the number of QRS complexes detected over 10-second sample signals corresponding to reference (FHR_ref) and estimated (FHR_est) for each of the 5 different women.

Woman	FHR_ref (in bpm)	FHR_est (in bpm)	Error (in %)
1	132	132	0
2	141	129	8
3	132	105	20
4	126	126	0
5	150	165	10

4. DISCUSSION

Assessment of the FHR for fetal monitoring is routinely performed as an important part of antepartum and intrapartum care. The results of this study have shown that the FHR can be determined directly from abdominal recordings with a good accuracy and without the need of recording of any reference signal. Nevertheless, to obtain more satisfactory results, thus, better accuracy, signals (reference and abdominal) should be carefully recorded. The high errors obtained for women 3 and 5 are mainly due to the fact that both reference and abdominal signals were very noisy which severely affected the separation performance of the ICA and therefore the overall results. In fact, given that very few abdominal signals are used as ICA inputs, it is important that at least one of the signals recorded, comprising the FECG, has high enough SNR in order to increase the accuracy of our proposed approach since the artifacts may populate most of the ICs thus causing the separation of the desired sources to fail.
Still to be tested, we believe that the problem is worthy of much further improvement, mostly by improving the quality of the recordings and by increasing the number of abdominal electrodes. Finally, we believe that the proposed approach can be a very powerful technique which can be used, not only to evaluate the FHR, but also to extract the FECG signal.

5. CONCLUSION

In this work, we investigated the ability of combining BSS and adaptive filtering in order to evaluate the FHR directly from the composite abdominal signals. From this study, we first conclude that FHR can be successfully determined from few abdominal composite signals without the use of any reference signal. The results obtained are promising compared to previously reported results based on recording the maternal ECG signal by separate electrodes. The proposed approach may be further extended to extract the FECG signal.

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