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Fetal ECG Extraction from Multichannel Abdominal ECG Recordings for Health Monitoring During Labor

Viorel Ionescu[a,*]

[a]*Department of Physics and Electronics, Ovidius University, Constanta, 900527, Romania*

Abstract

Extracting clean fetal electrocardiogram (fECG) signals from non-invasive abdominal ECG recordings for monitoring the health of the fetus during pregnancy and labor remains a big challenge. The proposed system for facing extraction, processing and morphological feature estimation was implemented in LabVIEW 2013 with preinstalled Biosignal Filtering, Advanced Signal Processing and Digital Filter Design Toolboxes. The present approach is based on the using of FastICA algorithm for fECG extraction. In order to improve fECG extraction performance, it was applied here a combination of Undecimated Wavelet Transform (UWT) and Fast Fourier Transform (FFT) – Inverse Fast Fourier Transform (IFFT) algorithm as post-processing tool. Fetal ECG morphological indicators like heart rate, T/QRS ratio and QT interval could be estimated from fECG post-processed signals of two patients and some considerations regarding to the fetal stress during labor could be made in these two cases.

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Keywords: fetal electrocardiogram; ICA algorithm; extraction; wavelet transform; QT interval.

1. Introduction

One of the major problems in modern obstetrics is the much reduced possibility to extract valid information about the health of the fetus from various monitoring methods during labor. Along the pregnancy, fetal heart rate (FHR) can be monitored noninvasively using Doppler ultrasound. Unfortunately, this technique is inaccurate and provides a

* Corresponding author. Tel.: +40-766-653755
E-mail address: v_ionescu@univ-ovidius.ro

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relatively low positive predictive value [1]. Cardiotocography (CTG) with continuous monitoring of FHR and uterine contractions is worldwide the method for fetal surveillance during labor, being used in addition with fetal blood sampling (FBS) technique. FBS it requires expertise, is invasive and has to be repeated when CTG abnormalities persist and can cause complications [2].

Performing a fetal electrocardiogram (FECG) waveform analysis, it can be obtained useful information about the physiological state of the fetus. Fetal ECG morphological features can be identified with success using an invasive method by means of an electrode connected to the fetal scalp. Unfortunately, this direct measurement of the FECG has a major drawback, being applied only during labor after rupture of the membranes. FECG can be extracted also from the abdominal electrocardiogram (aECG) recordings by means of multiple electrodes placed on the abdomen of the mother. The reliability of fetal cardiac parameters extracted aECG recordings and their excellent agreement with the values obtained from a scalp electrode signal has been recently demonstrated [3].

Electrophysiological signals presented in each measurement are maternal electrocardiogram (message), fECG and electrohysterogram (EHG) which is electrical activity of the uterus, very intense during labor. Fetal ECG is mixed with other sources of disturbance like maternal muscular noise, respiration, skin resistance interference, acoustic noise produced by fetal movements and power line disturbance so fetal ECG extraction from abdominal recordings of a mother is a very challenging task.

So far, different signal processing techniques have been applied for the extraction of the fetal ECG for non-invasive recordings. One of the most common is Independent Component Analysis (ICA) based on various algorithms, mathematically described by A. Hyvarinen and E. Oja [4]. The Fast ICA algorithm and INFOMAX ICA algorithm [5], along with JADE ICA algorithm [6] were successively used for FECG extraction from multichannel ECG recordings. The ICA MERMAID algorithm was proposed by D.E. Marrosero et al. [7] for eight channel recordings.

Utilization of ICA alone for extraction and processing of fECG signals has practical limitations due to very high noise affecting these signals. In order to overcome such limitations, ICA has been utilized in conjunction with discrete wavelet decomposition [8] and JADE ICA algorithm completed with wavelet post processing for baseline removal and dancing was applied to five sensors aECG recordings [9].

During fetal ECG monitoring in labor, the key features are FHR rhythm-related and QRST morphology related. For example, when fetal ECG is recorded intrapartum with a scalp electrode, changes in the T wave and the ST segment of the ECG could automatically be identified and analyzed using the STAN S21 monitor [10]. Recently, J. Reinhard et al. [11] reported successful non-invasive abdominal fetal electrocardiography on 6 patients during delivery, using 5 abdominally sited electrodes (Monica AN24). P and QRS waves were seen in all cases and T waves in 3/6 (50%).

2. Methodology

In this paper, it was used a collection of multichannel electrocardiogram (ECG) recordings obtained from two different women in labor between 38 and 41 weeks of gestation, referred from now on as *patient 1* and *patient 2*. Those recordings were accessed from Abdominal and Direct Fetal Electrocardiogram Database available on PhysioNet [12], being acquired in the Department of Obstetrics at the Medical University of Silesia by means of the KOMPOREL system for acquisition and analysis of the fetal electrocardiogram (ITAM Institute, Zabrze, Poland). Each recording comprises four different signals acquired from maternal abdomen and the reference direct fetal electrocardiogram registered from the fetal head. All recordings with a total duration of 5 minutes were sampled at 1 kHz and were encoded on 16 bits.

The system diagram for fetal electrocardiogram extraction and morphological features investigation is depicted in Fig. 1.

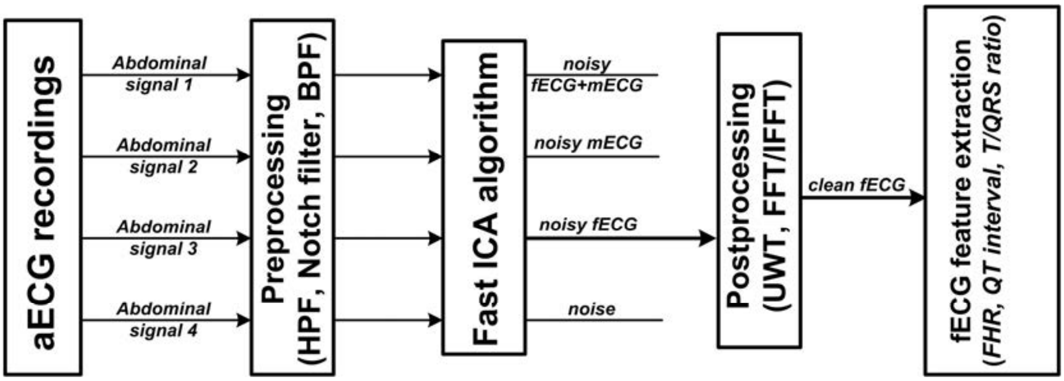

Fig.1. Block diagram of the proposed approach

2.1. Preprocessing stage

The spectrum of EHG signal presented in each typically ranges between 0.1 Hz and 3Hz [13]. For a suppression of baseline wandering and cancellation of most of EHG we used a high pass FIR digital filter based on Kaiser Window with stop band edge frequency of 0.5 Hz and passband edge frequency of 3Hz, implemented using Biosignal Filtering VI LabVIEW module.

The power line interference is a narrow band noise centered at 50 Hz with a bandwidth less than 1Hz. In order to suppress this type of noise, we used a sharp notch filter (with Q-factor equal to 30) at 50 Hz, selected from DFD IIR Notch peak design VI of LabVIEW Digital Filter Design Toolkit.

Next, for reducing high frequency noises coming from motion artifacts we implemented a 100th order IIR Butterworth band-pass filter from DFD Kaiser Design VI, with a bandwidth range of 0.5 – 34 Hz because the frequencies of interest for PQRST wave extraction are located mainly in this domain.

2.2. Independent Component Analysis technique

Independent Component Analysis (ICA) is a statistical analysis technique used to decompose a multivariable signal into a set of mutually independent, non-Gaussian components, assuming that the measured signals are a combination of independent source signals described mathematically by the ICA model [4]:

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

were $x = [x_1, x_2, \ldots\ldots, x_M]^T$ is the observed multivariate signal, $s = [s_1, s_2, \ldots\ldots, s_N]^T$ 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.

The aim of ICA is to return the linear unmixing matrix W in order to acquire the estimated Independent Components y such that:

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

The FastICA has most of the advantages of neural algorithms: it is parallel, distributed, computationally simple, and requires little memory space and the independent components can be estimated one by one, which is roughly equivalent to doing projection pursuing [4].

The Advanced Signal Processing Toolbox provided TSA (*Time Sample Analysis*) Independent Component Analysis VI with which fastICA algorithm was easily adopted due to its convergence speed.

2.3. Post-processing stage

Wavelets transform de-noising stage using biorthogonal 4.4. wavelet function at five levels of decomposition improved the FastICA extraction quality for ECG signals[14]. In order to suppress wideband noise from ICA extracted fECG signals we used Undecimated Wavelet Transform (UWT) from Wavelet Denoise Express VI. To get a better identification of the acquired signal, biorthogonal 4.4 wavelet filter at eight levels of decomposition was chosen, its scaling function being closely related to the shape of the ECG.

Unfortunately, after successfully wavelet transforms de-noising, some noise component was still present and in order to improve signal-to-noise (SNR) value further filtering technique is absolutely necessary. For this purpose, we implemented a signal processing pair formed by Fast Fourier Transform (FFT) and Inverse Fast Fourier Transform (IFFT) using FFT VI and Inverse FFT VI from Signal Processing Palette. Using FFT transform, signals were converted from time to frequency domain, high and low frequency components being sorted out to indicate the unwanted noise components. The signal is isolated from the initial and last *5*fft_lenght/sampling rate* samples in the frequency domain and thus filtered. Applying after that IFFT, filtered signal is reconverted to the time domain and became ready for the feature extraction process.

2.4. Fetal ECG features extraction stage

For fECG feature extraction with the purpose of detecting RT and QS time locations and maximum amplitudes, we used a combination of Peak Detector VI from Signal Operation Palette and WA Multiscale Peak Detection VI from Wavelet Analysis Palette.

FHR could be detected automatically for various time intervals of recordings using Extract Heart Rate SubVI.

3. Results and discussions

To emphasize the significance of FFT-IFFT, in fig. 2 was presented a post-processed fECG signal before and after time domain / frequency domain /time domain conversion for *patient 2*. It can be seen that after FFT/IFFT processing, noises with a maximum amplitude of about 2 μV peaks to peak located at 3.35 s - 3.45 s were nicely smoothed. Otherwise, this noise can be mistaken with a fetal heartbeat of similar amplitude located at about 3 s and can produce an unwanted error in the evaluation of R-R interval and FHR.

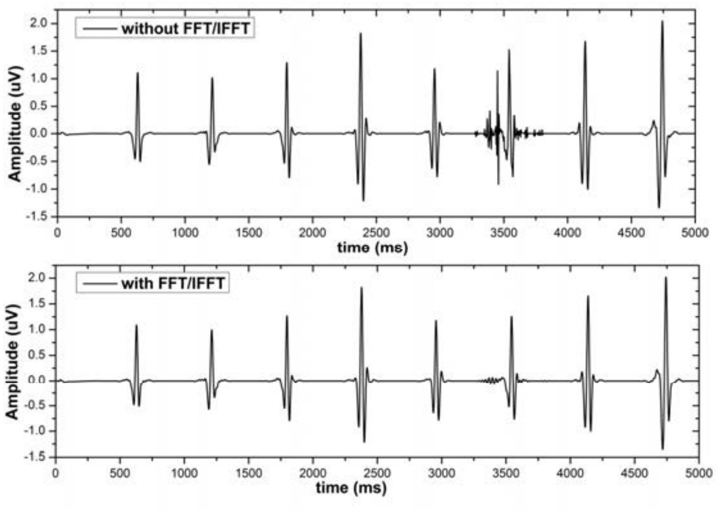

Fig.2. Comparison of preprocessing approaches with and without FFT/IFFT algorithm applied to a fECG signal extracted from patient 2 (in recorded interval of 1.23 min – 1.28 min).

In fig. 3, extracted and post-processed fetal ECG signal registered from *patient 1* was compared with a reference fECG signal obtained invasively from a scalp electrode. We could observe from here very good features similitude between the two fECG signals. Upper graph from fig. 3 contain the mixed mECG/fECG source signal extracted by Fast ICA algorithm, before the post - processing stage. Completely noise free mECG extracted signal was presented here after post-processing stage, offering the possibility of an eventual mother health monitoring after PQRST feature extraction.

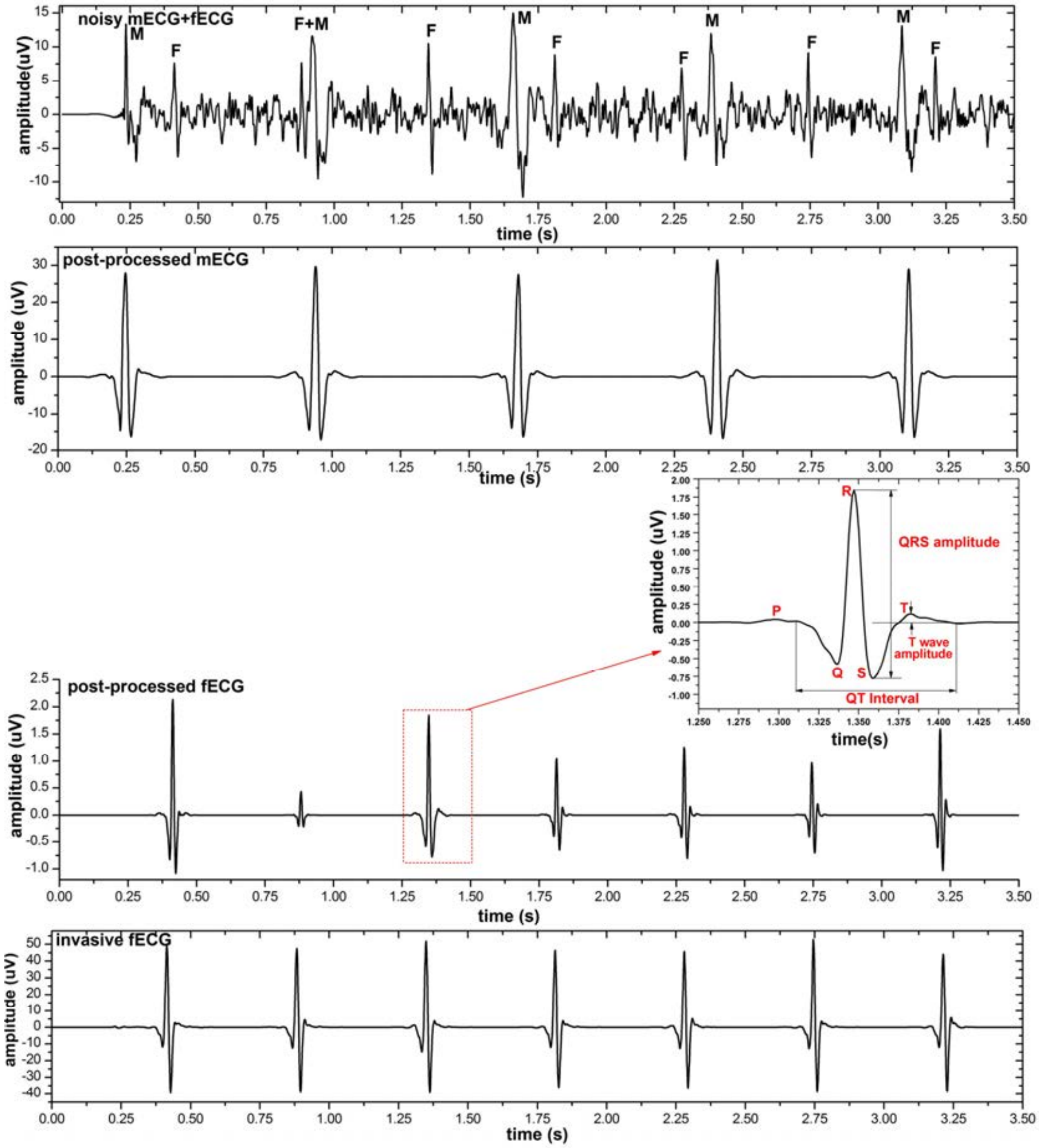

Fig.3. Maternal and fetal ECG signal after post-processing stage, extracted from aECG recordings of patient 1 in time interval of 0 s -3.5s. The lower graph showed a direct facing of the same patient, registered with an invasive method. Fetal and maternal heart beats in the upper graph are labeled F and M, respectively.

Previous studies showed that the average T/QRS ratio of the fetal ECG obtained during labor from 25 women with normal pregnancies ranged from 0.04 to 0.23, with a mean of 0.1 [15]. A normal T/QRS amplitude ratio less than 0.25 predicting normal fetal acid-base status (99.3% of the time) provided reassurance that any FHR abnormality was not clinically significant [16]. It was reported also in the literature that the fetus has a fairly stable T/QRS ratio throughout labor [17, 18]. The fetus tries to adapt to changes in its environment and most of FHR variation are not related to oxygen deficiency.

M. A. Oudjik et al. [19] reported in the case of a term fetus monitored invasively with STAN S21 fetal monitor throughout labor a sudden drop in heart rate from 150 BPM to 70-80 BPM associated with a rise of the T / QRS ratio and a shortening of the QT interval. In this case, an emergency vacuum extraction was performed. It has been shown from a case study of 68 patients that a significant shortening of the QT interval was associated with intrapartum hypoxia (resulting in metabolic acidosis) irrespectively of changes in FHR, whereas in normal labor these changes do not occur [19].

After those considerations, at first it was performed a monitoring of fetal cardiac rate for the two patients along the entire period of fECG registration, as we could see from fig.4. For both patients it was observed the apparition of moderate bradycardia (FHR between 75 and 85 BPM) along some ten second intervals under study. *Patient 1* presented a 20 BPM fetal heart rate drop in interval 2.00 min – 2.10 min of monitoring (see fig.4.a). Mild bradycardia (mean FHR of 80 or 90 BPM) with retention of beat-to-beat variability is common during the second stage of labor and not of great concern so long as delivery occurs relatively soon [20].

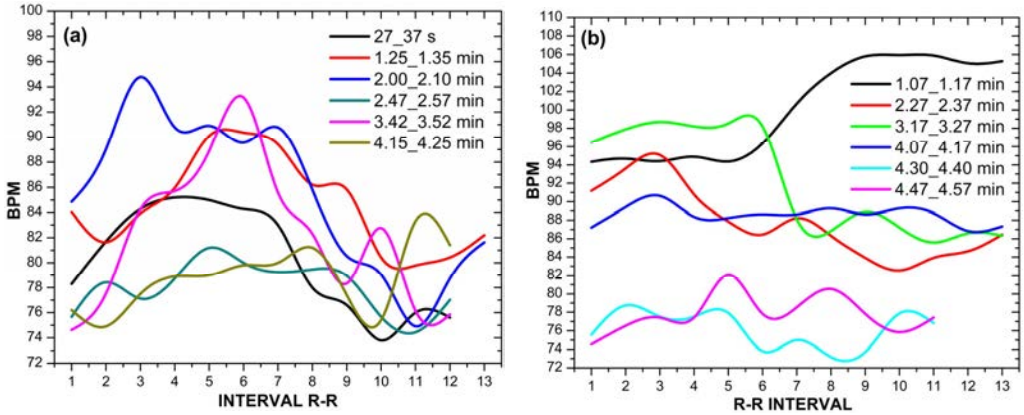

Fig.4. Fetal BPM rates for patient 1 (a) and patient 2 (b), estimated at six different time intervals during all the 5 minutes of recordings.

In order to establish the fetal health during labor with a certain degree, other ECG morphological investigations were necessary.

It was then studied in fig. 5 the evolution of the T / QRS ratio and QT interval for six cardiac cycles located at various times along the registration period.

From fig. 5.a it was observed for *patient 1* an increasing-decreasing evolution trend of T/QRS ratio between values of 0.028 and 0.098, QT interval having similar variation between 131 ms and 176 ms. In the case of *patient 2*, T/QRS ratio varied between 0.096 and 0.2 along the cardiac cycles monitored, with a mean value of 0.13; QT interval was maintaining approximately constant at 120 -130 ms, with one exception (154 ms for cardiac cycle located at 3.21 minutes).

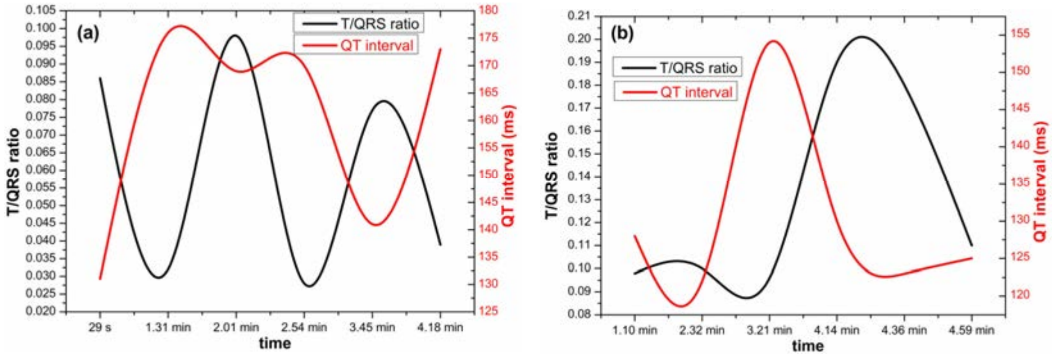

Fig.5. Evolution of T/QRS ratio and QT interval for six cardiac cycles located at various time values of fECG registration for patient 1(a) and patient 2(b).

4. Conclusions

The results of this study have shown that fetal electrocardiogram morphological parameters can be successively estimated after an extraction of fetal ECG signals from a collection of aECG recordings using Fast ICA algorithm and after a post-processing stage with wavelet transform and an FFT/IFFT pair.

For very weak fECG signals, FFT/IFFT processing system can be very useful, filtering noises up to 1 μV in amplitude which can affect the correct estimation of R-R intervals.

FHR monitoring correlated with the evolution of the T / QRS ratio and QT interval couldn't indicate an advanced fetal distress with possible intrapartum hypoxia for the two fetuses during the five minutes of fECG registering.

This non-invasive morphological fECG analysis method for intra-partum monitoring does not reduce the incidence of metabolic acidosis, but can reduce the incidence of emergency cesarean deliveries and the need for fetal blood sampling from umbilical artery.

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