Fetal Survey via Abdominal Recorded Signals

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***Abstract* – Fetal heart rate (fHR) and the morphological features of the fetal ECG (fECG) can be derived from (fECG) signals recorded on the maternal abdomen. However, when assessing the fECG through the abdominal signals (ADS), it's very low amplitude causes a problem, since the fECG representation in the ADS is buried in a mixture of other signals with stronger energy. Thus, signal to noise ratio of these recordings is low, the maternal electrocardiogram (mECG) being the main interference component. The aim of the present paper is to evaluate the performance of an algorithm for maternal ECG (mECG) subtraction. The performance of the algorithm considered in this study is evaluated by applying it on both simulated and real ADS signals.**

***Index Terms* – abdominal recordings, fetal monitoring, fetal electrocardiogram, subtraction algorithm.**

I. INTRODUCTION

Antepartum and intrapartum fetal surveillance constitute an essential component of the standards for evaluating and analyzing the health state of the fetus during pregnancy and labor.

Hypoxia is one the most frequently form of fetal distress during pregnancy. The state of hypoxia appears when the oxygen supply to the fetus through the placenta is affected, leading to ischemia or in the worst case to asphyxia. There are numerous causes for hypoxia from maternal disorders like: anemia, heart diseases, chronicle lung diseases, to placental disorders, the high stress which is put on the fetus during labor and high consumption of drugs, e.g. cocaine. The effects of oxygen deprivation are different according with the terms of pregnancy, thus on early terms it leads to congenital abnormalities, myocardial thinning, late development of embryo [1] whereas on late terms leads to intrauterine growth restriction and brain damage. The latter can be the cause of psychiatric and neurologic disorders in adulthood [2], [3] and of behavioral and cognitive deficits in childhood [4], [5]. However, it is not clear what is the timing and the duration of a fetal hypoxic exposure that can have as outcome a specific behavioral, cognitive, and emotional sequel in childhood and adulthood. Nevertheless, the early identification of hypoxic distress is mandatory for maintaining the health state of the fetus.

Another disorder which can appear during pregnancy is congenital heart defects which represent the leading cause of birth defect-related deaths [6]. It affects 35,000 infants, i.e one out every 125 infants born in United States [7] and one out 145 infants born in United Kingdom [8]. Congenital heart defects represent structural problems, malformations of the heart which are present at birth. Usually they occur during heart development, due to a mishap, soon after conception and often before the mother is aware of the pregnancy. The consequence of the defects may range from simple problems, such as "holes" between chambers of the heart, to very severe malformations, such as complete absence of one or more chambers or valves. Moreover, congenital heart defects can also increase the risk of developing certain medical conditions like: congestive heart failure, pulmonary hypertension, arrhythmias, anticoagulation [6].

Nowadays, fetal monitoring is based entirely on the fetal heart rate (fHR) analysis and does not incorporate characteristics of the fetal electrocardiogram (fECG) waveform, which represent the keystones of cardiac evaluation of both children and adults.

The morphological characteristic analysis of the fECG can identify both hypoxic episodes and congenital heart disorders described above. Thus, the ST segment is very sensitive to metabolic dysfunction induced by fetal hypoxia: an increase in T wave, quantified by the ratio of the T wave to the QRS amplitude (T/QRS ratio), or a biphasic ST pattern [9], [10], [11]. By combining these morphological changes of the fECG with fHR analysis, additional clinical information is provided to the physicians, leading thus to minimization of the unnecessary obstetric interventions.

The fECG constitutes the access to both fHR and the waveform of the electrical activity of the fetal heart. However, the standard procedure used nowadays for recording the fECG is by placing an electrode, invasively, on the head of the fetus, after the rupture of the amniotic sack. This recording method has some major drawbacks because it is cumbersome, it can put in danger the life of both the mother and the fetus and it is only applicable during delivery.

Thus, abdominal recorded signal (ADS) represent an alternative, as it is noninvasive, provides clinically significant information concerning the health state of the fetus through the analysis of the FHR and the morphology of the fECG. Moreover, it can also be used for long term monitoring.

Nevertheless, the fundamental problem is that ADS represents a multi-component signal containing several other disturbing signals of high amplitudes besides the low amplitude fECG component.

Among these perturbing biosignals, the maternal ECG (mECG) is clearly the main source of disturbance. The transabdominal fECG R-peak amplitude ranges from 10 to 100 μV, whereas the amplitude of the QRS complex of the mECG shows 0.5 to 1 mV [12]. Other disturbing signals which must be considered are the electronic noise (introduced by amplifiers etc), the slow baseline wander of signals (mainly due to electrode effects), the myoelectric crosstalk from abdominal muscles, and, in particular during labor, the uterine contractions. The large amplitudes of these noise sources are hiding the transabdominal fECG and a

simple high-pass filtering of ADS for fECG extraction cannot be applied due to the overlapping spectra of the fECG and of the noise components.

All these effects reveal evidently that reliable methods for removing the mECG are necessary to allow fECG examination based on ADS recordings. This demand motivates the development of several methods supporting the extraction of the low amplitude fECG from ADS for fHR computation, such as principal component analysis [13], independent component analysis [14] and nonlinear state projections algorithms [15]. But the increasing interest of physicians to consider not only the instantaneous fHR but also the waveform of the fECG introduces new signal processing requirements, thus (linear) filtering methods in general are getting more demanded. For this purpose, our paper reports about the evaluation of the performances of an improved linear method, on simulated and real ADS data.

II. METHOD

The algorithm described in this paper was developed in Matlab version 7.0.1 and consists of two steps: maternal QRS detection and mECG extraction. The flow chart of the algorithm is presented in Fig.1

A. Detection of the maternal QRS complex

In order to detect the maternal QRS (mQRS), an additional signal is generating as following: the ADS is filtered by a bandpass extracting the frequency range of (5÷11) Hz which covers the QRS complex in the ECG mainly. Thus, the P- and T-waves as well as the EHG are attenuated.

The filters used to generate the additional signal that identifies the QRS complexes are described by the following equations:

$$y(n) = 2y(n-1) - y(n-2) + x(n) - \\ - 2x(n-6) + x(n-12) \quad (1)$$

for the first filter (LP), and:

$$y(n) = x(n-16) - \\ - \frac{1}{32}[y(n-1) + x(n) - x(n-32)] \quad (2)$$

for the second filter (HP), as proposed in [9].

Subsequently, the derivate is applied:

$$y(n) = \frac{1}{10}[2 \cdot x(n) + x(n-1) - x(n-3) - 2 \cdot x(n-4)] \quad (3)$$

and then the resulting signal is squared in order to emphasize QRS complex.

Finally, a moving average window is applied; its window length covers a complete QRS complex which lasts about 100 ms. This additional signal is aligned with the original signal, considering the delay introduced by the previous processing techniques, and further a peak detection algorithm combined with a threshold determines its peaks corresponding to the mQRS complexes.

B. mECG removing

The mECG component is removed by applying the Event Synchronous Canceller (ESC) [16]. Each time an mQRS complex is detected in ADS, a template obtained by averaging of all mQRS segments centered on the R-peaks is subtracted from the ADS.

Since the uterine activity results in a change of the isoelectric line of the maternal QRS (mQRS) complex, it is necessary to adapt the isoelectric line in the averaged mQRS complex.

For calculating the optimal position of the averaged ECG template, first the information about the baseline wander is introduced in the template using linear interpolation. Then whenever the algorithm detects a mQRS complex, the optimal position of the template is determined by adjusting the template position, vertically and horizontally within a window of 15 samples centered on the considered mQRS (15 ms).

The minimum error of the fitting between the template and the mECG, considering only the mQRS, is taken into account in order to estimate the optimal position, as the miss-positioning of the QRS template often leads to a remaining maternal QRS, comparable with the fetal QRS and thus the morphology of the fECG is no longer conserved. This way, the current mQRS is replaced by a segment including only the random noise from the ADSs, with zero mean.

Based on the interpolated isoelectric line, the denoised ADS is combined with the raw data, preserving the continuity of the signal.

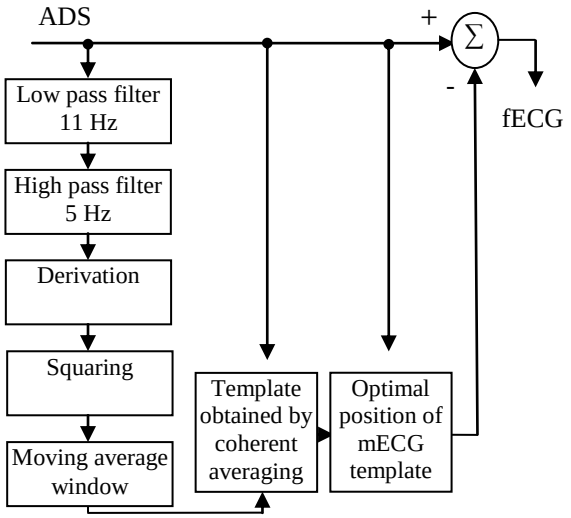

Fig. 1. Flow chart of the algorithm describing the detection of QRS complexes in ADS and the mECG extraction with the recovery of the isoelectric line.

III. DATA DESCRIPTION

The algorithm was applied on both simulated and real signals.

C. Simulated signals

The abdominal signals are simulated using the model described in [17].

The generation of the morphology of the simulated ECG cycles is realized using the three differential equations, (4), which represent the motion equations in 3D around a unit circle placed in xy-plane. On this circle five distinct points are placed at fixed angles, $\theta_P, \theta_Q, \theta_R, \theta_S, \theta_T$ in order to generate the P, Q, R, S, T waves.

$$\dot{x} = a \cdot x - \omega \cdot y$$
$$\dot{y} = a \cdot y - \omega \cdot x \quad (4)$$
$$\dot{z} = -\sum_{i \in \{P,Q,R,S,T\}} a_i \cdot \alpha_i \cdot \Delta\theta_i \cdot \exp\left(-\frac{\Delta\theta_i^2}{2 \cdot b_i^2}\right) - (z - z_0)$$

Thus the waveform is made to move away from the isoelectric line, i.e. the unit circle in the xy-plane, near the fixed points which behave like repellors, having a Gaussian morphology [16]:

where $\alpha = 1 - \sqrt{x^2 + y^2}$, $\theta = \text{atan}^2(y/x)$, $\Delta\theta_i = \theta - \theta_i$ and ω is the angular velocity of the time vector as it moves around the limit circle; a_i contains the amplitude of the waves and b_i contains the width of each wave.

D.Real data

The real data are recorded with the Biopac MP150 acquisition system from a healthy woman; gestational age is 34 weeks and the sampling frequency is 1000Hz.

Ten electrodes are placed on the maternal abdomen as depicted in Fig.2.

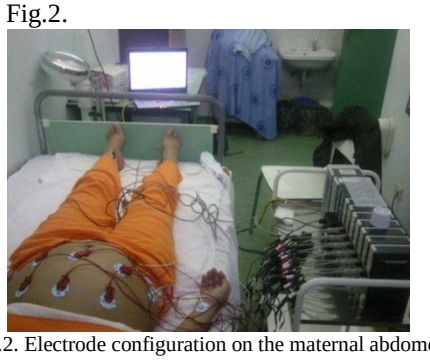

Fig.2. Electrode configuration on the maternal abdomen

IV. RESULTS AND DISCUSSIONS

E.Results on simulated data

A segment of the simulated data used to evaluate the performance of the algorithm is depicted in Fig. 3.

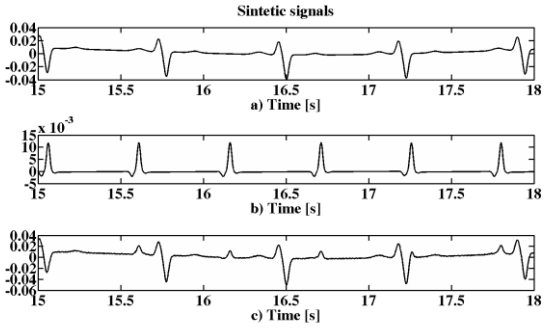

Fig. 3. Simulated ADS signals: a) mECG simulated by the dynamic model; b) fECG simulated by the dynamic model; c) simulated ADS. Note: arbitrary units are used for *y* axis.

In Fig. 4 the detection of the mQRS complexes can be observed.

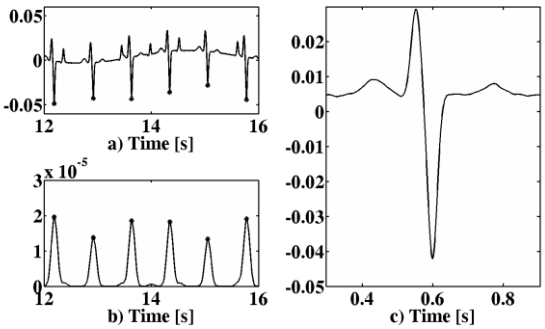

Fig. 4. mECG template estimation from simulated ADS data: a) detection of the maternal R-peaks; b) Auxiliary signal used for QRS detection; c) extracted mECG template.

The results of the fECG extraction by applying the ESC to the simulated data are depicted in Fig. 5. As depicted in Fig. 5, the mECG is completely removed, even when overlapping the fECG; the cleaned ADS signal still shows the maternal respiration, introduced as a disturbance in the simulated ADS.

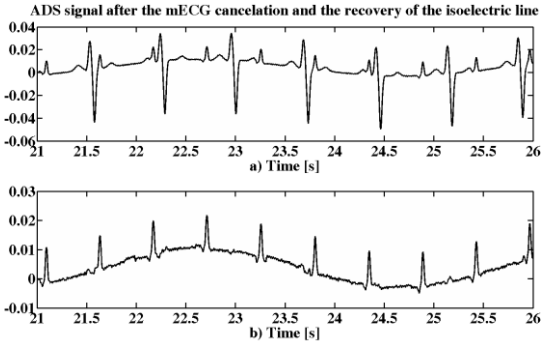

Fig. 5. fECG extraction from simulated ADS: a) simulated ADS signal; b) extracted fECG, after mECG cancelling by ESC.

F. Results obtained on real data

In Fig. 6 the detection of the mQRS from real abdominal recorded signals can be observed, whereas in Fig. 7 the cancelation of the mECG is depicted, without disturbing the shape of any overlapping fECG.

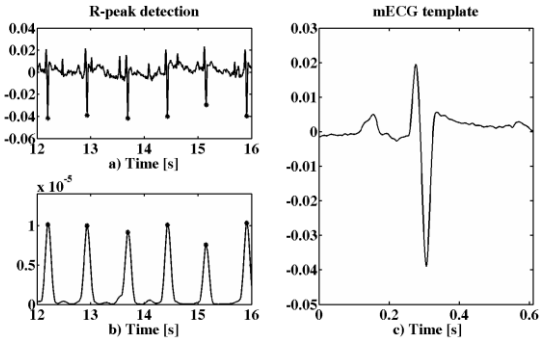

Fig. 6. mECG template estimation from real ADS data: a) detection of the maternal R-peaks; b) Auxiliary signal used for QRS detection; c) extracted mECG template.

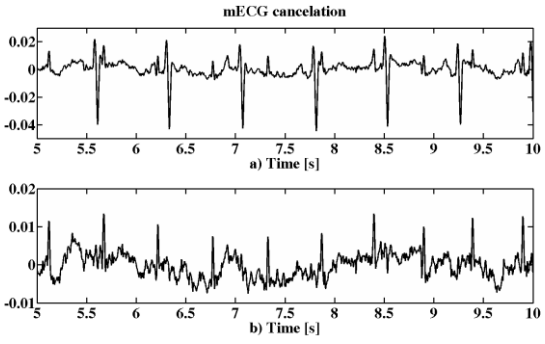

Fig. 7. The fECG extraction from real ADS (normal pregnancy, 37wk): a) real ADS; b) extracted fECG, after mECG cancelling by ESC. Note: arbitrary units are used for *y* axis.

The algorithm described in Section II shows very good results, as demonstrated in Fig. 5 and 7 and its performance is evaluated by calculating the error between the original simulated fECG and the extracted fECG, with:

$$\varepsilon_{fECG} = \frac{\sum \left(fECG_{orig} - fECG_{extracted} \right)^2}{\sum fECG_{orig}^{\ 2}} = 0.0379 \quad (5)$$

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