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Monitoring the Fetal Heart Rate Variations by Means of Time-Variant Multivariate Analysis

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***Abstract*— The analysis of the fetal heart rate (fHR) is important in detecting the fetal distress related with hypoxic episodes, noticed sometimes during the uterine activity, which can severely affect the fetus. Occasional synchrony between the fHR and the maternal heart rate (mHR) was reported and the mHR shows some variations during pregnancy and labor, especially when the contractions are very strong. The current study proposes a new strategy to investigate the relations between the fHR, the mHR and the uterine activity, by applying the time-variant Partial Directed Coherence (tvPDC).**

I. Introduction

The way that the maternal heart rate (mHR), fetal heart rate (fHR) and uterine activity (called electrohysterogram - EHG when measured noninvasively by abdominal recordings) are connected is still not fully discovered and efforts are involved lately to identify the interdependence between these signals [1-4].

Recently it was reported that the fetal accelerations occurred simultaneously with uterine contractions only in 11.7 and 4% of cardiotocograph fetal heart rate (fHR) and scalp fHR, respectively [1].

Occasional coupling between fetal and maternal cardiac systems was noticed [2] and it was also suggested that the fetal cardiac system has the capability to adjust its rate in response to maternal stimulation, or generally, to external stimulation [3-5].

The mHR varies during pregnancy and labor, high mHR values being recorded during labor, when the strong uterine activity is detected [6]. fHR detection using abdominal fetal ECG is reported as more reliable and accurate than ultrasound fHR, since abdominal recordings are less likely to display the maternal heart rate instead of the fetal heart rate, as compared to the ultrasound recordings [7] (the fetal scalp electrode as a reference method [7]).

Regarding the investigation of the directed connectivity, it is not clear yet whether nonlinear measures perform better than the linear ones [8]. To extract the directed interactions, linear methods like Granger Causality Index – GCI [10], and Partial Directed Coherence – PDC [10] or nonlinear methods, are usually applied, the processing being performed in time [9], in frequency [10], or in time-frequency domain respectively.

The time-frequency causality analysis deals with the problem of non-stationary signals, which can be also solved by considering the time varying GCI or PDC [10]. Even if the effective connectivity detection was considered in biomedical engineering mainly for the investigation of the brain [8]-[10], lately the investigation of the information transfer flow in cardiovascular and cardio-respiratory signals, by nonlinear and linear [11] time-invariant approaches, is considered. The time-variant causal analysis, that allows the extraction of the time-varying directed connections, would be of high interest since it allows the investigation of hypoxia during pregnancy, which irreversible affects the fetus [12].

The current study analyzes the directed influence among fHR, mHR and EHG, in the time-frequency domain, based on time-variant Partial Directed Coherence (tvPDC).

II. Data Description

The datasets used in the current study is recorded with Biopac MP150 acquisition system at the Cantacuzino Hospital in Bucharest, Romania. The recording setup contain 10 unipolar abdominal channels, with the reference electrode placed on the back [13], where no fECG is expected, and the 1st and the 2nd maternal ECG (mECG) leads, recorded over 10 minutes, at a sampling frequency of 1000 Hz. The ground electrode is placed on the right hip (see Fig. 1). The gain of the BIOPAC amplifiers was 5000 and the low pass and high pass BIOPAC filters were applied (cutoff frequency 300 Hz and 0.05 Hz, respectively). The fetal ECG (fECG) is quite clear all the time, in the channels 1-7 and 10, having a high signal-to-noise ration in channels 2, 3, 5 and 6.

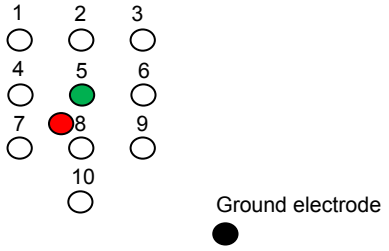

Figure 1. Electrodes placement for unipolar abdominal recordings: 10 electrodes placed on the maternal abdomen, 1 reference electrode (RED) on the back, on the opposite side of electrode 5 (placed near the navel), and the ground electrode (BLACK) on the right hip. The distance between the electrodes is 10 cm.

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III. DATA PROCESSING AND SIGNAL ANALYSIS

In order to investigate the relation between the mHR, fHR, and the EHG signal, the following preprocessing steps are considered: i) the channels are high-pass filtered at 300 Hz and a comb filter is applied to remove the power line interferences, for the ECG analysis; ii) the mHR is estimated and based on the detected maternal QRSs, the Event Synchronous Canceller is then applied to remove the main disturbing signal, the maternal ECG, to obtain the cleaned abdominal signals (ADS) is obtained at this stage, containing mainly the signal of interest, the fECG; iii) the fHR is estimated based on the cleaned ADS, using for example the ICA and the ESC method [14]; iv) the EHG is obtained by high-pass filtering the ADSs at 5 Hz; the channel with the most relevant uterine activity is selected after that; v) the relation between the mHR, fHR and EHG is investigated by considering the tvPDC.

A. Event Synchronous Canceller

One way to easily remove a repetitive noise source is by applying the Event Synchronous Canceller (ESC) [14]. When applied on ADSs, it efficiently removes the mECG, allowing the fECG recovery.

The ESC involves two steps. i) Firstly, the mECG template is obtained as the averaged abdominal mECG, considering all the detected mECG segments in the ADS. The maternal QRS complexes can be detected by using an additional maternal ECG lead, not disturbed by the other physiological signals contained by the ADS; the current study considers this extra channel to allow the accurate mECG detection. ii) Then, the estimated mECG template is subtracted from the ADS, whenever a maternal QRS is detected, the other signals remaining undisturbed; i.e., the fECG morphology is preserved, allowing the analysis of the fECG waves and segments.

The mECG peak detection can be performed by thresholding technique, by considering some filtering stages, as in the Pan-Tompkins algorithm, or by applying the Wavelet transform [15].

In the current study the maternal QRS detection is simply done using a thresholding strategy. The maternal template includes the linear and non-linear distortions of the maternal ECG signal, due to the signal path and the recording techniques.

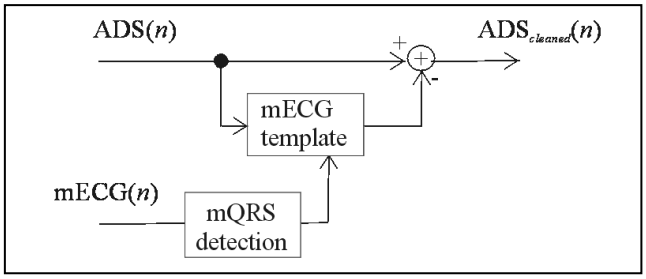

Figure 2. The ESC. The mECG template of the repetitive disturbing component, the mECG, is constructed from the ADS channel by event triggered averaging, being then subtracted from the ADS channel.

B. Linear modeling – multivariate autoregressive model

Let us consider that the direct influences among N channels (signals) $y_i, i = \overline{1,N}$, are to be investigated, having K trials available. Then, the linear model is described by:

$$\mathbf{x}(n) = \sum_{k=1}^{p} \mathbf{A}_k(n) \cdot \mathbf{x}(n-k) + \boldsymbol{\varepsilon}(n), \quad \mathbf{A}_k(n), \boldsymbol{\varepsilon}(n) \in \Re^N \tag{1}$$

where the time-variant coefficients are obtained by applying the Recursive Least Square (RLS) algorithm which assumes the following cost function:

$$E_n = \sum_{i=1}^{n} (1-c)^{n-i} \left\| \mathbf{z}_i \right\|^2 \ , \ 0 < c < 1 \tag{2}$$

The steps of the RLS algorithm are:

$$\begin{aligned} \hat{\mathbf{A}}_n &= \hat{\mathbf{A}}_{n-1} + \mathbf{Z}_n^T \cdot \mathbf{K}_n \\ \mathbf{K}_n &= \mathbf{W}_n \cdot \mathbf{C}_n \\ \mathbf{C}_n &= \left[(1-c)^n \mathbf{I}_{Mp} + \sum_{i=1}^{n} (1-c)^{n-i} \mathbf{W}_i^T \cdot \mathbf{W}_i \right]^{-1} \\ \mathbf{Z}_n &= \mathbf{X}(n) - \mathbf{W}_n \cdot \hat{\mathbf{A}}_{n-1}^T \end{aligned} \tag{3}$$

with:

$$\mathbf{W}_n = \left(\mathbf{Y}_{n-1}, \ldots, \mathbf{Y}_{n-p} \right) \in \Re^{K \times Mp}$$

$$\hat{\mathbf{A}}_n = \left(\mathbf{A}_1, \ldots, \mathbf{A}_p \right) \in \Re^{M \times Mp}$$

$$\mathbf{X}_n = \begin{bmatrix} x_1^{(1)}(n) & \cdots & x_M^{(1)}(n) \\ x_1^{(2)}(n) & \cdots & x_M^{(2)}(n) \\ \cdots & \cdots & \cdots \\ x_1^{(K)}(n) & \cdots & x_M^{(K)}(n) \end{bmatrix} \in \Re^{K \times M}$$

The time-variant effective connectivity analysis is preferred, since analyzed real signals are usually nonstationary; the order has to be carefully selected, since the available AR order selection criteria (Akaike information criterion - AIC, Bayesian information criterion – BIC, etc) assumes the signal stationarity:

$$AIC(m) = 2 \log\left(\det(\Sigma)\right) + \frac{2p^2 m}{N_{total}} \tag{4}$$

$$BIC(m) = 2 \log\left(\det(\Sigma)\right) + \frac{2p^2 m \log N_{total}}{N_{total}} \tag{5}$$

Some additional spectrum fitting of the parametric spectrum could improve the order estimation criteria.

C. Partial Directed Coherence

The Partial Directed Coherence (PDC) [11] is a powerful method that investigates the effective connectivity in the

frequency domain and is evaluated based on the Autoregressive (AR) parameters by:

$$\bar{\pi}_{ij}(\omega) = \frac{\bar{A}_{ij}(\omega)}{\sqrt{\bar{\mathbf{a}}_j^H(\omega) \cdot \bar{\mathbf{a}}_j(\omega)}} \quad (6)$$

with:

$$\bar{\mathbf{A}}(\omega) = \mathrm{I} - \mathbf{A}(\omega) = [\bar{\mathbf{a}}_1(\omega) \quad \bar{\mathbf{a}}_2(\omega) \quad \cdots \quad \bar{\mathbf{a}}_M(\omega)]$$

$$A_{kl}(\omega) = \delta_{kl} - \sum_{r=1}^{p} \hat{a}_{kl,r} e^{-i\omega r} \quad .$$

The PDC id defined by considering the partial directed coherence factor (PDCF) defined as bellow, but avoiding mixing the Granger Causality with instantaneous Granger Causality.

$$\bar{\pi}_{ij}(\omega) = \frac{\bar{A}_{ij}(\omega)}{\sqrt{\bar{\mathbf{a}}_j^H(\omega) \Sigma^{-1} \bar{\mathbf{a}}_j(\omega)}} \quad (7)$$

Σ is the covariance matrix of $\varepsilon_i(n)$, i.e. the prediction error covariance matrix of the MVAR model defined by (1), $A(\omega) = \sum_{k=1}^{p} \mathbf{A}_k \cdot z^{-k}\Big|_{z=e^{-j\omega}}$ and $\mathbf{A}_k$ is defined by [11]:

$$\mathbf{A}_k = \begin{bmatrix} a_{11}(k) & \cdots & \cdots & \cdots & a_{1N}(k) \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & a_{ij}(k) & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{N1}(k) & \cdots & \cdots & \cdots & a_{NN}(k) \end{bmatrix}$$

The performance in effective connectivity estimation depends mainly on improving the estimation of the parameters.

When the AR parameters are estimated as time-varying values, the PDC allows the investigation of the effective connectivity in time and frequency domain.

IV. Results and Discussions

The analyzed data were recorded on a normal pregnant woman, with a normal fetus (38 weeks - gestational age). The instantaneous fHR and mHR were computed, and resampled at 10 Hz, which allows the extraction of the EHG signal, with frequency components up to 3Hz [14]. The DC components were thereafter removed, to allow the investigation of the directed connection among the fHR, mHR and EHG (Fig. 3).

In order to extract the fHR and the mHR, the thresholding peak detection algorithm is considered, and a correction using the median filtering is applied in the computation of the instantaneous fHR, to correct the fetal QRS misdetection during the uterine activity (each time a misdetection occurs, the HR rate is corrected by using the value provided by the median filtering technique).

The instantaneous fHR is estimated after the ESC algorithm is applied on abdominal signals, to remove the main disturbance, the mECG, to allow a better application of the ICA algorithm, in order to compute the fHR.

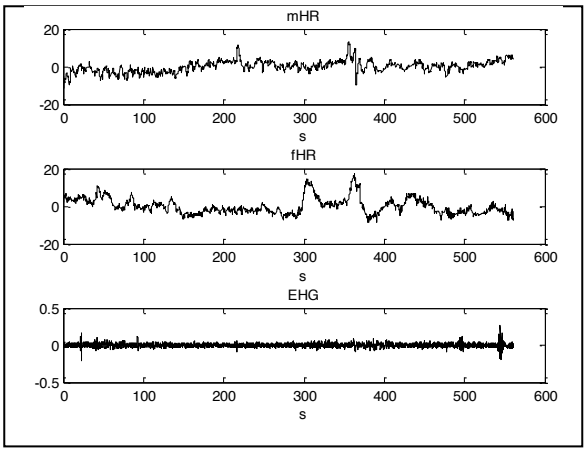

Figure 3. The computed mHR, fHR and the estimated EHG, after removing the DC component.

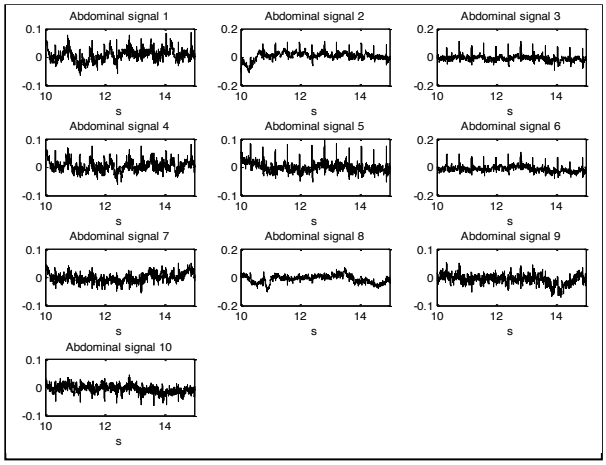

Figure 4. The 10 abdominal signal channels after removing the mECG by independently applying the ESC (a.u. for the *y* axis).

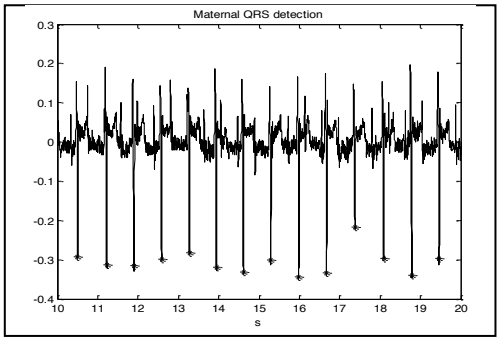

Figure 5. Detected mQRSs, to apply the ESC and to compute the mHR (a.u. for the *y* axis).

Fig. 4 presents a 5s length abdominal signal segment, with clear fECG in the channels 2, 3, 5 and 6. The results of the peak detection algorithm when considering the mECG and the fECG are shown in Fig. 5 and Fig. 6, respectively.

Since the ESC algorithm removes only the mECG signal from the ADSs, and not the other disturbing sources (EHG, abdominal EMG, electronic noise, baseline wander, and power line interference [14]), the ICA-JADE algorithm is applied, for an accurate instantaneous fHR computation, considering the ICA fECG component(s) (Fig. 7).

The results after applying the tvPDC are shown in Fig. 8, revealing the influence of the uterine activity on the fHR and mHR, as expected by the physicians. No relation between the mHR and the fHR was detected within the 10 min analyzed dataset.

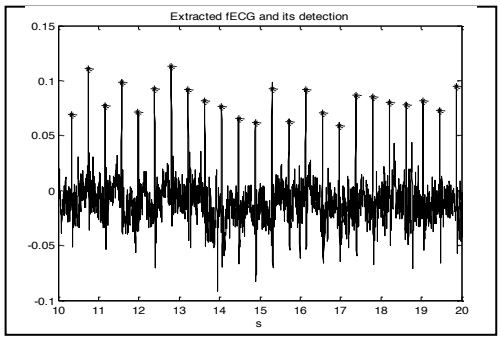

Figure 6. The cleaned abdominal signal, and the fQRS detection, to estimate the fHR. a.u. for the *y* axis.

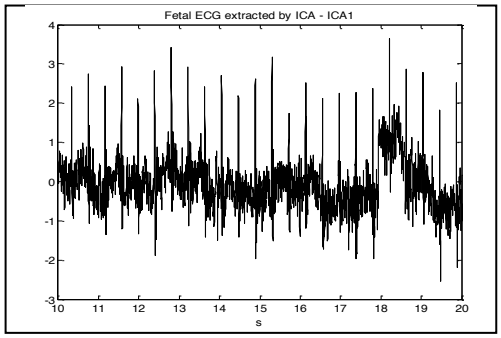

Figure 7. The 1st ICA component extracted by the JADE algorithm. It contains the best extracted fECG signal.

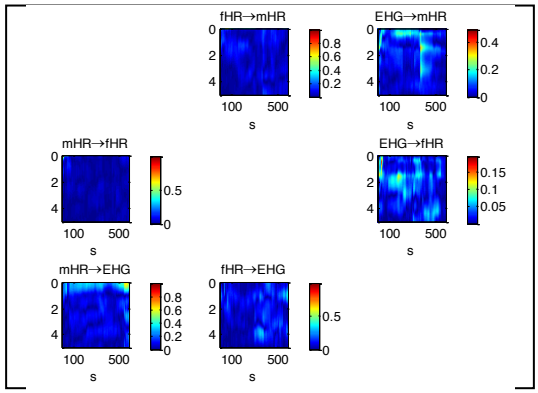

Figure 8. The connectivity between the fHR and the EHG. As physiologically expected, the influence of the EHG is stressed. Hz on *y* axis.

V. Conclusions and Discussions

Some influence from the EHG signal to the mHR was noticed at high frequencies and, as reported in the literature, the high frequencies components of the EHG being of interest for normal pregnancies around parturition [16]. The high frequency components of the uterine activity have sometimes influence over the fHR variability. The further investigations, considering more data, will contribute with the statistical evaluation of the directed connectivity among the fHR, mHR, and the EHG.

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