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# Foetal PQRST Extraction from ECG Recordings using Cyclostationarity-Based Source Separation Method

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**Abstract**—This work proposes a novel foetal electrocardiogram (FECG) extraction approach based on the cyclostationary properties of the signal of interest. The problem of FECG extraction can easily fit in a blind source separation (BSS) framework; taking into account specific statistical nature of the signal, that one wants to extract, leads to an algorithm able to estimate the FECG contribution to ECG recordings where the maternal ECG is predominant. We show that the proposed procedure provides estimates of the FECGs PQRST complexes without incorporating any prior knowledge concerning PQRST features. Discussions about foetal heart rate variability (HRV) estimation and future works conclude this paper.

## I. INTRODUCTION

Given its numerous fields of application, the problem of source separation has been extensively investigated these last few decades [1], [2], [3], [4]. It copes with the possibility of retrieving one specific source from a set of sensors. The method is based on the assumption that the different sources reach the sensors through different propagation paths, so that the resulting mixtures are different. Different scenarios can be found, depending on the type of propagation and the hypotheses that can be made about the nature of the sources. Indeed, the sources can be either filtered (convolutive mixtures) by the propagation paths, or they can be delayed equally or not at all (instantaneous mixtures), which gives different mixture models. The classical hypothesis for the blind separation is independence of the sources, which leads to criteria based on second order and higher order statistics.

Here we address the problem of extracting one specific source rather than separating all the sources. This can be described by the classical equations given below. Let  $\mathbf{s}(t) = [s_1(t), s_2(t), \dots, s_N(t)]^\top$  denote the source vector with  $\top$  the transpose operator. These sources can be the mother's or the foetus' heartbeats, the breathing and other physical phenomena that generate some electromagnetic variations. We suppose that at least as many sensors as sources, i.e.  $N$ , are available and the observations can be brought together in an observation vector  $\mathbf{x}(t) = [x_1(t), x_2(t), \dots, x_N(t)]^\top$ . The attenuation due to the different propagation paths can

be modelled as a  $N \times N$  matrix  $A$ , called *mixing matrix*, which relates the observations to the sources:

$$\mathbf{x}(t) = A\mathbf{s}(t). \quad (1)$$

Let us suppose, without any loss of generality, that the source to be extracted, i.e. the foetus' heartbeats, is the source  $s_1(t)$ . The extraction then consists in estimating a vector  $B = [b_1, b_2, \dots, b_N]$  such that  $z(t) = B\mathbf{x}(t)$  is an estimate of  $s_1(t)$ . The method we propose is simple and it is based on the measured value of the foetal heartbeat rate and on second order statistics. As it will be shown further, it leads to an accurate estimation.

## II. DATA AND METHOD

### A. Experimental Data

The dataset to which we applied the cyclostationary-based source separation method is the well-known *DalSy* database [5]. It consists of eight electrocardiogram recordings (Fig. 1). Each of them represents a 5 sec length signal as captured by skin electrodes placed at different locations in the pregnant woman's body. The first five signals come from electrodes placed in the mother's abdominal region; the last three are obtained from mother's thoracic region. The sampling rate is 500 Hz and the eight observations are recorded simultaneously.

The mother's contribution to these ECGs is clearly visible in the last three signals contrary to the foetus' contribution which is dominated by the maternal ECG. This is mainly due to the much longer path taken by the signal generated from the foetus' heart until it arrives to the mother's chest located electrode. The electrical activity of the foetal heart is also disturbed by other noise signals, such as, the 50 Hz power line interference, random electronic noise due to the instrumentation and baseline wandering [6].

The aim of the blind source separation technique we describe hereafter is to extract the signal of interest, i.e. the FECG, from a set of observations, also called *mixtures*.

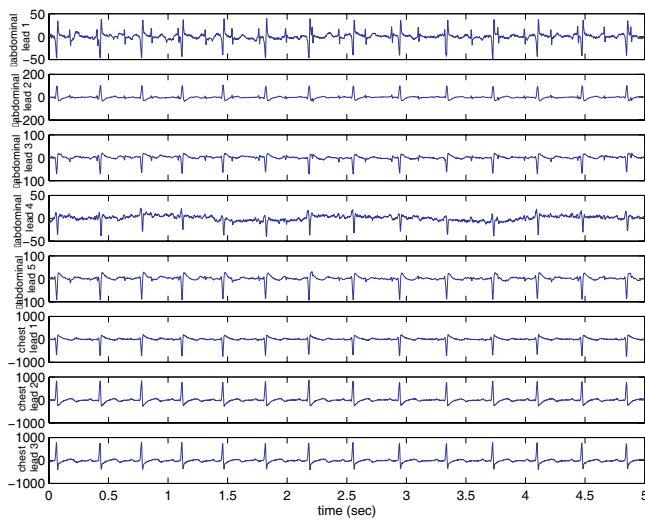


Fig. 1. Eight cutaneous electrode recordings from a pregnant woman

### B. Proposed Extraction Method

It has been shown in the literature that, under some assumptions concerning ECG's effective frequency and the distance between electrodes and the cardiac sources [2], [7], ECG recordings can be modelled as linear instantaneous additive mixtures. Moreover, artifacts introduced by breath and shift positions, and the propagation medium being time-varying, the stationary mixing is not always a good approximation [7].

Our algorithm is based on the assumption that the foetus' heartbeat, if not strictly periodic, is at least repetitive, i.e. cyclostationary, at a frequency  $\alpha_0$  that can be measured from the recordings. The extraction criterion is based on the hypothesis that no other source is cyclostationary at the same frequency, which is a realistic one since the mother's heartbeats and her breathing, for instance, are much slower phenomena. The criterion  $C(B)$  to minimise is the ratio between the power  $|P_z|$  of the estimate and its *cyclic* power  $|P_z^{\alpha_0}|$  at frequency  $\alpha_0$ :

$$C(B) = \left| \frac{P_z(B)}{P_z^{\alpha_0}(B)} \right|. \quad (2)$$

When a noiseless additive mixture model can be assumed, this criterion has been shown in [8] to exhibit a unique minimum over  $B$  which leads to the extraction of the cyclostationary source corresponding to the selected cyclic frequency. The source is retrieved with an indeterminacy over its amplitude, but its contribution to the observations could then be estimated by further processing.

The criterion (2) can be estimated from the observations and the matrix  $B$  by the expression:

$$\hat{C}(B) = \left| \frac{B\hat{R}_{\mathbf{x}}(0)B^\dagger}{B\hat{R}_{\mathbf{x}}^{\alpha_0}(0)B^\dagger} \right| \quad (3)$$

where  $\hat{R}_{\mathbf{x}}(0) = \langle \mathbf{x}(t)\mathbf{x}^\dagger(t) \rangle_\theta$  and  $\hat{R}_{\mathbf{x}}^{\alpha_0}(0) = \langle \mathbf{x}(t)\mathbf{x}^\dagger(t)e^{-2\pi j\alpha_0 t} \rangle_\theta$  are the estimates of the covariance

matrix of the observations and their cyclic covariance matrix at frequency  $\alpha_0$ , respectively, and  $\langle \cdot \rangle_\theta$  stands for the temporal averaging over  $\theta$  seconds.

### C. Cyclic Frequency Estimation

A survey of the literature on cyclostationarity can be found in [9]. The method we used in order to estimate the cyclic frequency of the foetus' heartbeats is based on two assumptions. First, that the foetal heartbeat rate is greater than the mother's one and, second, that the dominant component of all the recordings is the mother's heartbeat one. Based on these two hypotheses, the foetal heartbeat rate can be measured from a plot of the envelope spectra of the observations.

The envelope spectrum of a signal  $s(t)$  is computed following the next three steps :

- Apply the Hilbert transform to  $s(t)$ , in order to generate the analytical signal  $\tilde{s}(t)$ .
- Compute the squared module of the analytical signal  $|\tilde{s}(t)|^2$ .
- Apply Fourier transform to this squared analytical signal.

Working on the analytical signal instead of  $s(t)$  itself, ensures that the high frequencies generated by squaring the signal do not lead to aliasing.

The envelope spectrum has been shown [10] to be a simple and efficient mean for detecting cyclostationary components, which produce spectral lines. If computed over the ECG signals measured on a pregnant woman's abdomen, one can expect to observe a strong family of spectral lines corresponding to the mother's heartbeats and a smaller one, at a higher rate, whose fundamental frequency is the foetal heartbeat rate.

The envelope spectrum of the first ECG channel is displayed on Fig. 2. The mother's heartbeat is the dominant phenomenon and produces a family of strong harmonic spectral lines whose fundamental frequency gives the average mother's heartbeat rate. A smaller spectral line appears between the first and second harmonics of the mother's component, which we suppose to correspond to the foetal

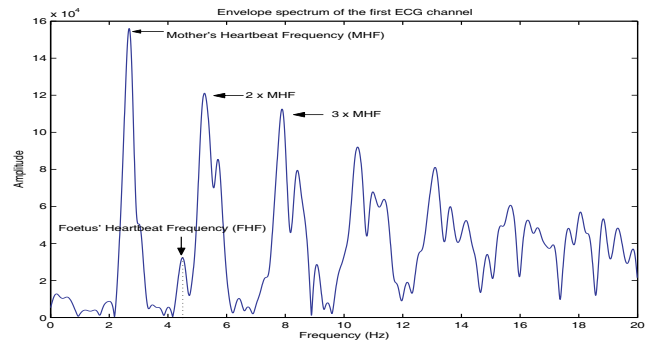


Fig. 2. Zoom on the envelope spectrum of the first ECG channel: a mean of computing the foetus's heartbeats cyclic frequency  $\alpha_0$ .

heartbeat rate. We measured the frequency at its maximum and used it as the extraction cyclic frequency; we hence estimated  $\alpha_0$  around  $4.49 \text{ Hz}$ . We first applied the algorithm to the whole set of 8 sensors and then to a set of 4 sensors placed on the mother's abdomen, i.e. close to the foetus. What follows is a discussion about the obtained results.

### III. RESULTS AND DISCUSSION

#### A. The Extracted Foetal ECG Signal

For our experiments, we used first the whole DaISy dataset and, then, selected four recordings :  $\mathbf{x}(t) = [x_1(t), x_2(t), x_3(t), x_5(t)]^\top$ . Each component of vector  $\mathbf{x}(t)$  is a 1-dimensional signal of 2500 samples. We considered signals from channels 1, 2, 3 and 5 because they are placed on the abdomen and the contribution of the foetal heartbeats to these channels is significant. Information from channel 4 has not been used as our other experiments have shown that it introduces a high baseline wandering effect into the extracted signal. The set of observations is the input vector to our extraction algorithm which then minimises the criterion  $C(B)$  and outputs an estimated FECG signal denoted  $z(t)$ . The only prior information the algorithm needs is the fundamental FECG cyclic frequency  $\alpha_0$ .

Fig. 3 shows the normalised extracted FECG signal after application of our algorithm ( $y$ -axis scale is arbitrary) to the  $\mathbf{x}(t)$  mixture vector (upper plot); for comparison purposes, we also plotted the normalised extracted FECG signal by using the whole recordings set (see section III-C for discussion). It exhibits 22 consecutive foetal heartbeat cycles. All these cycles are fairly cleared of interferences with mother's heartbeats or other noise sources. However, some artifacts still exist: a closer look near peaks around sample 2000 reveals the existence of lower height second peaks. One cannot say with certainty to which source of interference they do correspond. But the overall quality of the estimated FECG signal of interest is fairly good. Fig. 4 plots the spectra of the estimates; it can be seen that the mother's heartbeat (MHB) signal has been rejected from the 4 channel's estimate (top figure), except its first harmonic for the 8 channel's one (bottom figure).

Note, that, all BSS-based techniques estimate unknown source signals up to a sign term, permutation and amplitude

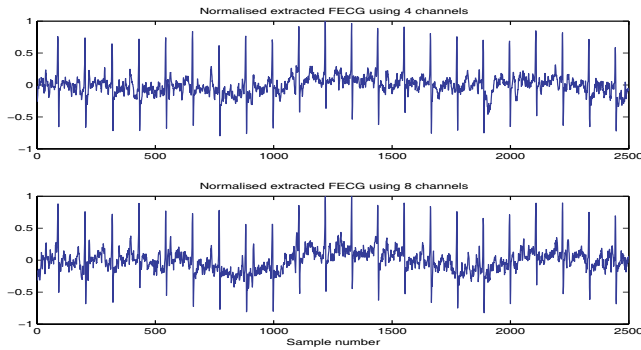


Fig. 3. The normalised extracted FECG signal, using four abdominal recordings (solid line) and all eight channels recordings (dash-dotted line).

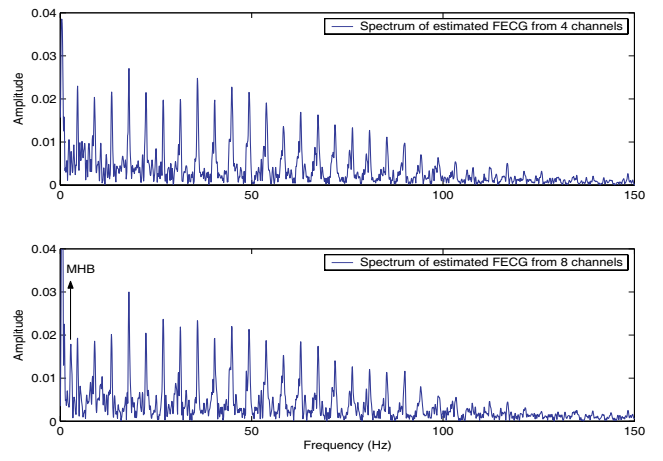


Fig. 4. Spectra of the extracted FECG signals by using 4 channel recordings (top) and 8 channel recordings (bottom).

scale. The advantage of the proposed technique is that we know, *a priori*, which signal is being estimated because we used its cyclostationary frequency to achieve our goal; so, we only extract the signal of interest. Also, expert eyes can easily decide which of the estimated signal  $z(t)$  and its opposite  $-z(t)$  is correct. Finally, the only indeterminacy that still persists is the one concerning the amplitude scale.

#### B. Foetal Heart Rate Variability

Foetal heart rate variability (fHRV) is an important parameter that can provide early information to clinicians about the well-being of the foetus. It is defined as the normal irregular changes and fluctuations in the foetal heart rate. Short- as well as long-term fHRV monitoring may be useful for early detection of possible troubles concerning the foetus' health during pregnancy. Thus, we try to measure HRV from the extracted FECG using 4 recordings of Fig. 3 by detecting the peak of larger amplitude value, and hence, computing the fHRV from sets of 2 consecutive beats. Given that there are 22 foetus's heartbeat cycles to the estimated FECG, one can see in Fig. 5, 21 plots of the same star-shape marker that provide an estimation of the fHRV. The trend of foetal's instantaneous heart rate [11] in this figure is not very clear.

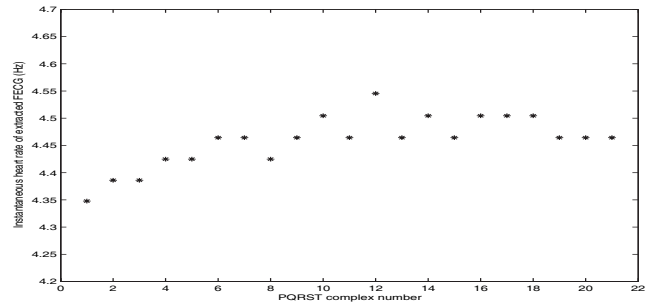


Fig. 5. Instantaneous heart rate from 22 consecutive foetus' heartbeat cycles of the extracted FECG signal

These last years, different source extraction and/or separation methods based on the periodic properties of the same ECG signals as the one we cope with, have been referenced in the literature. Jafari *et al.* [12] proved that, for periodic signals, the covariance matrix estimated for a time-lag equal to the fastest periodic component has properties that can be used for source separation. In [13], [14], Tsalaile *et al.* proposed to extract a periodic signal by jointly diagonalising correlation matrices at time lags proportional to the period of the source to be extracted. Sameni *et al.* [15] proposed a method which consists in maximising the periodicity of the extracted signal at the frequency of the source of interest. The extraction is performed by jointly diagonalising two correlation matrices computed respectively at zero time lag and at a time-lag corresponding to the period of the source to be extracted. These two methods take into account the HRV and a prior measure of each period duration is required, which is easy on the mothers heartbeats but involves pre-processing in the case of the foetus' heartbeat. Sameni *et al.* [16] presented an iterative algorithm that combines at each step both a diagonalisation/projection technique and a filtering technique in order to extract the components at the foetus' heartbeat rate. A periodicity measure is proposed in order to detect the mother's heartbeat interference on the estimate of the foetal one. This periodicity measure (PM) is given by :

$$PM = \frac{|E\{x(t)x(t + \tau_t)\}|}{\sqrt{E\{x(t)^2\}E\{x(t + \tau_t)^2\}}} * 100\%, \quad (4)$$

where the period  $\tau_t$  depends on time, in order to take into account the heartbeat rate variability ( $PM \in [0, 100]$ ).

The algorithm that we propose is simpler in that it requires only a measure of the mean cyclic frequency of the source to be extracted. In order to evaluate its performance we computed the PM proposed by Sameni *et al.* with the frequency of the mother's heartbeats. The results cannot be compared with the ones presented in [16] since we used a mean value of the period, but it allows the evaluation of the performances depending on the set of sensors used.

When the signal contains no component at the tested periodicity, the PM should be 0%. The PM obtained with the 8 sensors is equal to 6.4%, while with the 4 sensors it reaches 0.3%. This can be explained by the fact that the sensors placed on the mother's chest bring few new information about the foetus heartbeats, while a better extraction can be performed using only the abdomen ones.

#### IV. CONCLUSIONS

The novel FECG extraction algorithm presented in this paper is based on the property of cyclostationarity that ECG signals exhibit at the frequency of the foetal heartbeat rate. The extraction process uses a BSS scheme. The algorithm is tested on real pregnant woman's non-invasive ECG recordings and proved to provide fairly denoised FECG signal estimation. Yet, the estimated heart rate variability of the foetus is not robust enough for clinicians' use.

The obtained results are promising. Present and future research work consists in estimating the contribution of the extracted FECG signal of interest on each acquisition channel, testing the algorithm's robustness against variations of the fundamental FECG cyclic frequency  $\alpha_0$  and, improving the extraction procedure in order to obtain significant fHRV characterisation, as well as a direct comparison with results provided by other methods (e.g., [17]).

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