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Fetal electrocardiogram enhancement in abdominal recordings: recording setup analysis

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***Abstract*—The fetal electrocardiogram (fECG) obtained from the abdominal signals, to monitor the wellbeing of the fetus, is a weak signal, recorded by placing electrodes on the maternal abdomen surface. When recording the abdominal fECG, the main problem is to separate the fECG from the background noise, including the maternal electrocardiogram (mECG) and/or the power line interference (PLI), this leading to an improved fECG signal to noise ratio (SNR). This paper proposes and evaluates three types of recording configurations, having different reference location, and analyzes the performance of each recording setup, based on the corresponding SNRs, quantitatively evaluated. The fECG extraction is carried out in order to evaluate the performance of each proposed configuration.**

I. Introduction

Fetal monitoring during pregnancy is an important measure for the fetal wellbeing. The fetal monitoring methods have been improved in the last years, by using different ways to obtain biological signals that lead to fetal information. Many stressing conditions have a strong impact on the fetal well being change during pregnancy and labor, a careful monitoring of the fetus being mandatory; early detection of fetal condition abnormalities helps physicians to decide the medication accordingly and to take the proper decisions.

The abdominal fECG (ADS), obtained by placing electrodes on the maternal abdomen, represents an alternative to the clinical methods used for fetal monitoring. According to [1], the advantages of abdominal fetal ECG over the methods used nowadays in hospitals are: i) it is noninvasive; ii) it offers both the fetal heart rate and the morphology of the fECG signal; iii) it can be used for long term monitoring; iv) it offers, besides the fECG signal, the uterine contractions, the electrohisterogram signal (EHG), and the breathing movements.

The main drawback of this abdominal fECG signal is that there is no direct access to the fetus and the fECG recorded from the mother's abdomen is very weak due to the attenuation, caused by the propagation through multiple biological layers. Moreover, the fECG is corrupted by strong interferences such as: mECG, breathing movements, uterine contractions, power line interference (PLI), abdominal muscle contractions, i.e. the electromyogram.

Nevertheless, the fECG signal is strongly dependent on the configuration of the electrodes. Thus, the SNR regarding the fECG/mECG signals can be much improved just by optimally placing the electrodes. However, there are no standards or guidelines available in literature that discuss the best way in which the electrodes should be positioned or which type of recordings should be used: bipolar or unipolar.

There are several configurations reported in literature [2]-[7], but they differ from the type of measurement to the electrode location and placement of the reference electrode. Unipolar recordings seems to have more success in recording fECG but in this case it is not clear what is the best location for the reference electrode [3], [8].

The present study proposes a specific configuration of the electrodes and evaluates the best location of the reference electrode by computing the SNR regarding the fECG/mECG signals in different situations: i) the reference electrode is on the maternal back; ii) the reference is on the maternal hip; iii) the reference is near the navel.

The abdominal signals are generated using a mathematical model for generating simulated fECG and mECG signals. The proposed electrodes' placement allows also the six points approximation of the fECG Laplacian, which has the potential of improving the SNR, as demonstrated by the current study. An independent component analysis (ICA) algorithm is used to extract the fECG signal and to evaluate quantitatively the influence of the three proposed configurations.

II. Data Description

The simulated data used in this paper are generated using dimensional dynamic model of the electrical activity of the heart proposed by Sameni et al., [7], [9], to simulate the mECG and the fECG.

A new electrode configuration is proposed, to approximate the Laplacian in six points. When computing this placement, the maternal abdomen is approximated by a sphere having the center on the maternal back, the navel being considered as the origin of the cartesian coordinate system.

The coordinates of electrode locations on the sphere are computed with (1), considering the navel as the origin:

$$(x - x_0)^2 + (y - y_0)^2 + (z - z_0)^2 = r^2 \qquad (1)$$

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The abdominal signal computed for each electrode location depends on the maternal and fetal heart positions. Hence, the distances between the fetus heart and the location of the electrodes are considered and also the uniform attenuation of the fECG signal due to the biological tissues is assumed.

The cartesian coordinate representation of the dipole vector $d(t) = x(t) \cdot \bar{\imath} + y(t) \cdot \bar{\jmath} + z(t) \cdot \bar{k}$ can be applied on multi-channel ECG signals obtained on body surface, using a simplified model

$$\mathbf{ECG}(t) = \mathbf{H} * \mathbf{s}(t) + \mathbf{v}(t) \tag{2}$$

where ECG(t) is a vector of the ECG channels recorded at the N abdominal electrodes, $\mathbf{s}(t)$ contains the three orthogonal projections of the dipole vector $\mathbf{d}(t)$ on the axes, $\mathbf{v}(t)$ is the noise vector of the ECG channel and $\mathbf{H}$ is a time-variant matrix corresponding to the body volume, including the scaling and rotations of the dipole vector.

The orthogonal components are obtained using (3):

$$\dot{\theta} = \omega$$

$$\dot{x} = -\sum_i \frac{\propto_i^x \omega}{(b_i^x)^2} \Delta\theta_i^x \exp[-\frac{(\Delta\theta_i^x)^2}{2(b_i^x)^2}] \tag{3}$$

$$\dot{y} = -\sum_i \frac{\propto_i^x \omega}{(b_i^y)^2} \Delta\theta_i^y \exp[-\frac{(\Delta\theta_i^y)^2}{2(b_i^y)^2}]$$

$$\dot{z} = -\sum_i \frac{\propto_i^x \omega}{(b_i^z)^2} \Delta\theta_i^z \exp\left[-\frac{(\Delta\theta_i^z)^2}{2(b_i^z)^2}\right],$$

where ω is the angular velocity of the time vector as it moves around a limit unit circle, $\propto^x$, $\propto^y$, $\propto^z$ and $\mathbf{b}^x, \mathbf{b}^y$, $\mathbf{b}^z$represent the amplitudes and the widths, respectively, of the Gaussian functions, located at the rotational angles $\boldsymbol{\theta}^x, \boldsymbol{\theta}^y \, and \, \boldsymbol{\theta}^z$.

III. PROCESSING METHOD

Independent Component Analysis, ICA, is a linear decomposition method that aims to create a separation of a multiparameter signal into statistical independent components. The application of ICA in fECG extraction problem are studied in [10]-[12].

An ICA problem is defined by considering the following equation:

$$\mathbf{x} = \mathbf{A}\,\mathbf{s} + \mathbf{n} \tag{4}$$

where $\mathbf{n}$ is the uncorrelated Gaussian noise $\mathbf{n} \sim N(0, \mathrm{diag}(\sum))$, $\mathbf{x}$ is the observed random vector, $\mathbf{s}$ defines the sources and $\mathbf{A}$ the mixing matrix.

In the abdominal signal case, the signals recording by the electrodes are the observations and the signal generated by the fetal heart, maternal heart, abdominal muscles, uterine muscles, power line interference are the sources. The numbers of recording channels have to be higher than the number of sources.

The goal of ICA algorithms is to obtain an estimate of the sources and of the mixing matrix based on the observations. Good statistical performance is achieved by involving all the cumulants of order 2 and 4, while a fast optimization is obtained by the device of joint diagonalization, as described in [13],[14].

In the present paper JADE (Joint Approximate Diagonalization of Eigen-matrices) algorithm [14] is used for fECG extraction. The JADE algorithm has the following steps:

a) Initialization

The covariance matrix is defined as $\mathbf{R}_x$=E(X*X^T), where E is the mathematical expectation function and X the vector composed of observed signals. Denoting $\mathbf{D}$ as the diagonal matrix of its eigenvalues and $\mathbf{H}$ as the corresponding eigenvectors, a whitening matrix is computed:

$$\mathbf{W} = \mathbf{H} \cdot \mathbf{D}^{(-\frac{1}{2})} \cdot \mathbf{H}^{\mathrm{T}} \tag{5}$$

b) Estimation of a maximal set {Q_z} of the cumulant matrix.

Given a $n \times 1$ random vector $\mathbf{z}$ and any $n \times$ n matrix $\mathbf{M}$, the cumulant matrix is defined by:

$$Q_z(\mathbf{M}) = E(\mathbf{z}^T\mathbf{M}\mathbf{z})\mathbf{z}\mathbf{z}^T\} - \mathbf{R}_z tr(\mathbf{M}\mathbf{R}_z) - \mathbf{R}_z\mathbf{M}_z - \mathbf{R}_z\mathbf{M}^T\mathbf{R}_z \tag{6}$$

where *tr()* denotes the trace of the matrix.

c) Optimization of the orthogonal contrast.

A rotation matrix $\mathbf{U}$ is found at this step, such that the cumulant matrix is as diagonal as possible.

$$\mathbf{U} = argmin \sum_i Off(\mathbf{V}\mathbf{Q}_z\mathbf{U}) \tag{8}$$

*d) Estimation of the mixing array, **A***

$\mathbf{A}$ is computed as $\mathbf{V}$= $\mathbf{U}\mathbf{W}^{-1}$, and the sources as $\mathbf{V}$=$\mathbf{U}^{-1}\mathbf{X}$.

For the evaluation of the three electrode configuration proposed, the SNR regarding the fECG/mECG signals, $SNR_{fECG,mECG}$, is computed:

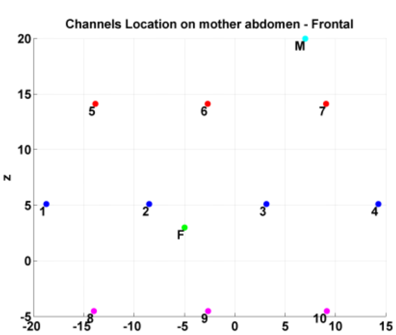
$$SNR_{fECG,mECG} = 20\log_{10}\left(\frac{A_{fECG}}{A_{mECG}}\right) \tag{9}$$

The Laplacian of the fECG is computed as following:

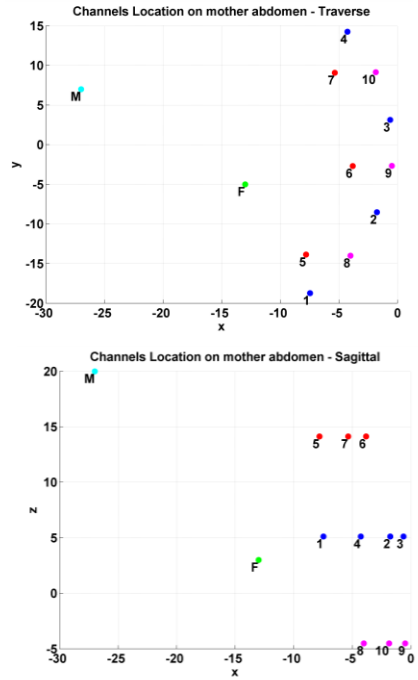
$$L_d = CH_L - \frac{1}{N}\sum_{i=1}^{N} CH_i \tag{10}$$

IV. RESULTS AND DISCUSSIONS

The positions of the abdominal electrodes, 1-10, are depicted in Fig. 1 according to the three orthogonal planes: transversal, longitudinal and sagittal, respectively. M stands for the maternal heart rate and F is the fetal heart rate.



a)



b)

c)

Figure 1. The proposed recording setup: a) Frontal plane of the electrodes placement; b) traverse plane of the electrodes placement;c) sagittal plane of the electrodes placement

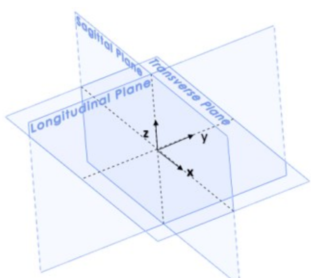


Figure 2. Representation of sagittal, transverse and longitudinal plane

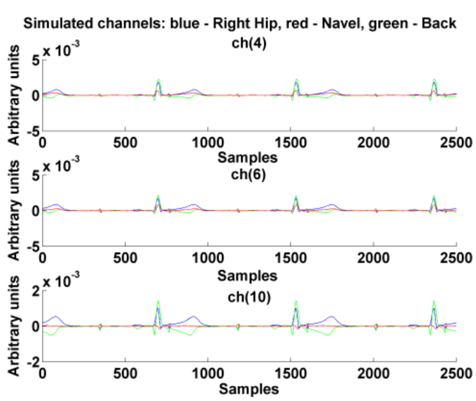


Figure 3. The simulated abdominal channels

In Fig. 3 and 4 are depicted the simulated signals obtained at each electrode location in the three different cases, reference electrode on the hip (blue), on the back (green) and near the navel (red).

In Table I the values of the $SNR_{fECG,mECG}$ in the three cases are presented.

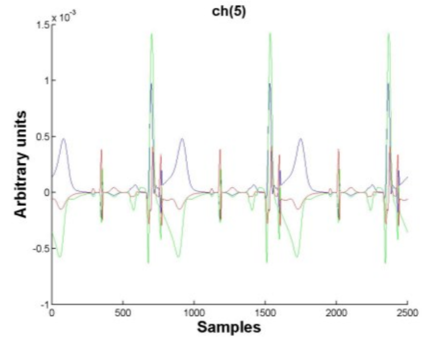


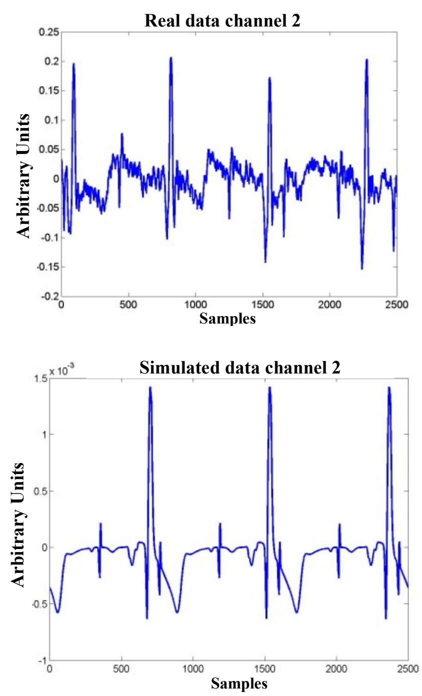
Figure 4. Comparison between simulated data on channel 5 using different reference: right hip (blue), navel (red) and back (green)

The highest $SNR_{fECG,mECG}$ is obtained when the reference electrode is placed near the navel. Moreover, the fECG in the case when the electrode reference is near the navel has slightly higher amplitude than in the other two cases. When analyzing the Laplacian output, we obtain a $SNR_{fECG,mECG}$ value of 7,61 dB. The $SNR_{fECG,mECG}$ is calculated using (9), where A_{fECG} and A_{mECG} are the amplitudes of R wave of the fetal and maternal ECG, respectively.

TABLE I. SIGNAL TO NOISE FECG/MECG

	Reference		
	Right Hip	***Navel***	***Back***
$SNR_{fECG,mECG}(db)$	-15,95	-6,95	-15,33

Fig. 5a depicts a real abdominal signal and in Fig.5b a simulated signal generated with the model presented in Section II can be observed. Both real and simulates signal have the reference placed on the maternal back.



a)

b)

Figure 5. Abdominal channel. a) Real data without PLI and b) simulated mECG and fECG included in the abdominal channel, with reference on the back

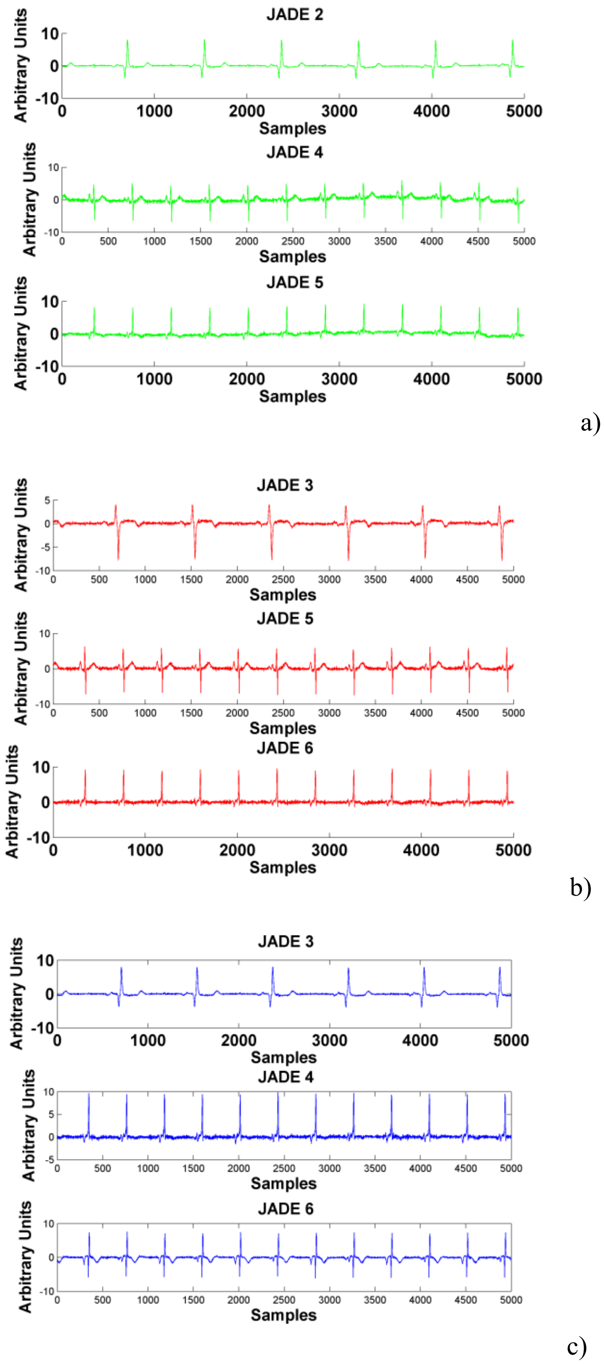


Figure 6. Independent components of ADS recording using the reference placed on thea) back, b) navel and c) hip

The JADE algorithm is applied on all three cases of simulated multi-channel fECG. The result are shown in Fig. 5 a, b and c. As depicted from the results in Fig. 5 a,b,c the fECG Independent Components, ICs, are not perfectly extracted. Hence, the maternal QRS is still present and it prevents the analysis of the fECG morphology. Nevertheless the FHR can be computed and thus the most important information about the wellbeing of the fetus can be obtained.

V. Conclusions

After analyzing the three types of configuration, and considering the best SNR, the study suggests that the use of the navel as the reference electrode is a good option, being expected to obtain better results when applying the fECG extraction algorithms or algorithms that cancel the mECG. The SNR obtained using the Laplacian calculus of ECG is very promising and it should require more research.

The use of blind source separation is interesting as it can help identify easily the fECG component, but further analysis has to be done in order to have clear information about the fetus wellbeing. It seems that the setup configuration does not affect the ICA algorithm performance. However, this is a preliminary study and a more detailed analysis has to be conducted to establish the best setup in order to have clear information about the fetus wellbeing.

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