Fetal ECG Extraction from Maternal Skin Electrodes Using Blind Source Separation and Adaptive Noise Cancellation Techniques

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Abstract

The extraction of the fetal electrocardiogram (FECG) from maternal cutaneous electrode recordings accepts a blind source separation (BSS) formulation. From this perspective, the problem reduces to the estimation of the independent sources of fetal cardiac bioelectric activity. In this contribution, a BSS method based on higher-order statistics is contrasted with a significant classical technique for FECG extraction, such as Widrow's multi-reference adaptive noise cancellation. As a best-case scenario, optimal Wiener-Hopf filtering solutions are considered for this latter method. Both procedures are applied to real multi-channel ECG recordings obtained from a pregnant woman. The experimental outcome demonstrates the more robust performance of the blind technique in this important biomedical application.

1. Introduction

Compared to conventional diagnostic techniques merely based on fetal cardiac rate estimation, the non-invasive extraction of the *antepartum* fetal electrocardiogram (FECG) from maternal cutaneous electrode recordings presents the potential benefit of offering more detailed information about the fetus' heart, thus allowing a more accurate diagnosis. The observation of the fetal heartbeat signals at the electrode output is hampered by a number of disturbances that corrupt the recordings, such as maternal ECG (MECG), EMG (e.g., due to uterus contraction) and respiration, mains coupling, thermal noise from the electronic equipment, etc. Appropriate signal processing techniques are required for recovering the wanted FECG components from the corrupted potential recordings.

In recent works, blind source separation (BSS) is arising as a promising approach to this biomedical application [1, 2]. From the BSS point of view, FECG extraction is achieved through the estimation of the independent sources of fetal cardiac bioelectric activity. The FECG source signals enable the reconstruction of the fetal heart components in the recordings, free from MECG and other disturbances. Nervertheless, the actual advantages of these techniques relative to other FECG-extraction procedures still need to be explored in detail.

In the present contribution, we establish a comparison between a BSS method based on higher-order statistics (HOS) and one of the most significant classical techniques for FECG extraction: Widrow's multi-reference adaptive noise cancelling (MRANC) method [3].

2. Experimental data

The real cutaneous electrode recordings[1] used in the experiments are plotted in Fig. 1. The signals were recorded at a sampling frequency of 500 Hz over 10 seconds from 8 electrodes located on a pregnant woman's skin. The first five recordings, in which a mixture of FECG, MECG and noise is visible, correspond to the mother's abdominal region. The last three signals were taken from the mother's thorax. Due to the longer distance between these latter electrodes and the fetal heart, no FECG heartbeat component can be perceived. Note that only the relative amplitudes of the vertical axes are important.

3. Methods

3.1. Blind source separation

According to an electrical model of the heart derived from the so-called lead-vector concept [1, 2, 4, 5], each of the p electrodes located on the patient's body, $\mathbf{y}(k) = [y_1(k),\, y_2(k),\, \ldots,\, y_p(k)]^\dagger \in \mathbb{R}^p$ (symbol k denotes a discrete-time index, and † the transpose operator), can be considered as an instantaneous linear combination of the different sources of bioelectric current. Assuming that all bioelectric activity is modelled by means of q unobservable statistically independent *source signals*, $\mathbf{x}(k) = [x_1(k),\, x_2(k),\, \ldots,\, x_q(k)]^\dagger \in \mathbb{R}^q$, the electrode

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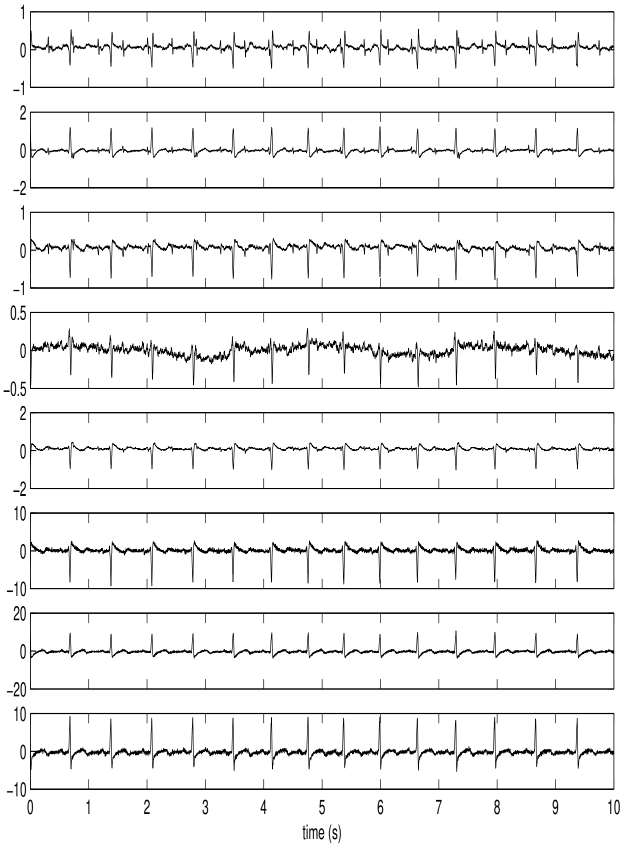

Figure 1. Cutaneous recording from a pregnant woman.

measurement vector accepts the matrix relationship:

$$\mathbf{y}(k) = M\mathbf{x}(k). \qquad (1)$$

Matrix $M \in \mathbb{R}^{p \times q}$ is the *mixing matrix*, with a structure determined by the body geometry and conductivity, as well as by the electrode-source relative positions [6]. Equation (1) is the BSS model of instantaneous linear mixtures [7].

The reconstruction of the FECG contributions to the recordings gets reduced to the identification of the independent sources of fetal cardiac activity and the corresponding elements of the mixing matrix. This goal requires first the estimation of the source signals $\mathbf{x}$ and the mixing matrix M through a suitable separation procedure. In these experiments, we consider the BSS method developed in [8] (see also [9] for its adaptive implementation). Essentially, the method operates in two steps. An initial principal component analysis (PCA) stage, also known as *pre-whitening*, produces a set of second-order uncorrelated signals $\mathbf{z} = [z_1, \ldots, z_q]^\dagger \in \mathbb{R}^q$. PCA is followed by a higher-order processing part — *independent component analysis (ICA)* [10] — aiming at higher-order independence. This latter stage is composed of elementary

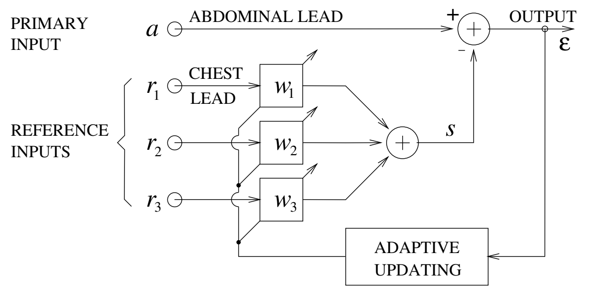

Figure 2. MRANC solution to FECG extraction.

Givens rotations, i.e., matrix transformations of the form $\widehat{Q} = \begin{bmatrix} \cos\hat{\theta} & -\sin\hat{\theta} \\ \sin\hat{\theta} & \cos\hat{\theta} \end{bmatrix}$, applied in turn to each pre-whitened signal pair $[z_i, z_j]^\dagger$. Rotation angles $\hat{\theta}$ characterizing such transformations are computed in closed form through a formula involving the 4th-order statistics of the data [8]. This pairwise process is repeated over all signal pairs until convergence.

3.2. Adaptive noise cancellation

Widrow's multi-reference adaptive filtering method was probably the most successful among the early approaches to FECG extraction [3]. An abdominal lead $a(k)$, mainly containing a mixture of FECG and MECG signals, acts as a primary input to an adaptive noise canceller (Fig. 2). The MECG interference corrupting the abdominal leads is considered as the 'noise' to be cancelled. The n reference inputs $\{r_i(k),\, i = 1, \ldots, n\}$ are thoracic leads, mostly composed of maternal heartbeat components. The reference inputs are adaptively processed by finite impulse response (FIR) filters $\{w_i(k),\, i = 1, \ldots, n\}$ of tap-length N, and subtracted from the primary input, the output at instant k being given by $\varepsilon(k) = a(k) - s(k)$, with $s(k) = \sum_{i=1}^{n} w_i(k) * r_i(k)$, where symbol '$*$' stands for the convolution operator. The adaption criterion whereby the filter coefficients are updated is the minimization of the output-signal power, or mean square error (MSE).

Practical implementations, such as the least mean square (LMS) method, are based on stochastic approximations of the above optimization criterion [11], which produce an MSE after convergence actually higher than the minimum MSE (MMSE) achievable for the given system parameters (misadjustment). MMSE performance is described by *Wiener-Hopf (WH)* solutions, whose mathematical formulation is well known [3]. Only second-order correlations of the reference signals and the primary sequence at different time lags are involved. For a given number of reference inputs n and filter taps N, the optimal impulse responses are the solutions in $\mathbf{w}_j \triangleq [w_j(0), w_j(1), \ldots, w_j(N-1)]^\dagger$ of the n linear

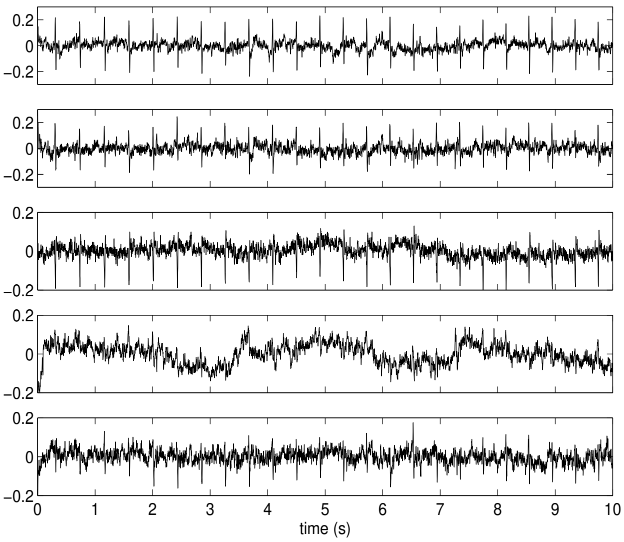

Figure 3. Fetal contributions to the abdominal electrodes (first five signals) of Fig. 1 obtained by the MRANC method.

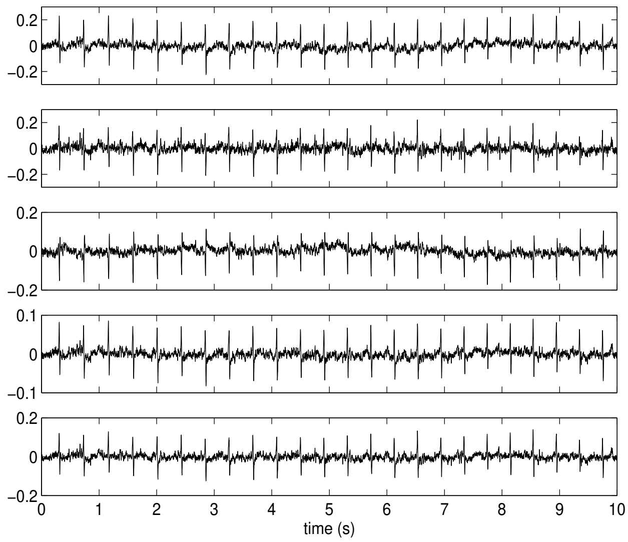

Figure 4. FECG contributions to the abdominal electrodes (first five signals) of Fig. 1 obtained by the BSS method.

systems

$$\sum_{j=1}^{n} R_{ij}\mathbf{w}_j = \mathbf{p}_i, \qquad i = 1, \ldots, n. \tag{2}$$

Matrices $R_{ij} \in \mathbb{R}^{N\times N}$ are built up as $R_{ij}(u, v) \triangleq \mathrm{E}[r_i(k-u+1)\, r_j(k-v+1)]$, and vectors $\mathbf{p}_i \in \mathbb{R}^N$ as $\mathbf{p}_i(u) \triangleq \mathrm{E}[r_i(k-u+1)\, a(k)]$, with $i, j = 1, \ldots, n$ and $u, v = 1, \ldots, N$.

4. Methodology and results

For Widrow's MRANC solution, the three thoracic leads of Fig. 1 are employed as reference inputs to the canceller (i.e., $n = 3$, as depicted in Fig. 2), whereas the five abdominal leads play (one after the other) the role of primary inputs. Optimal WH filters for $N = 50$ taps are calculated as indicated in Section 3.2 (see in [12] their impulse responses), providing the corresponding output waveforms displayed in Fig. 3.

For the BSS method, the independent source signals are estimated as described in Section 3.1 (their actual waveforms can be found in [12]). A simple visual inspection detects three maternal and two fetal sources, together with three other sources of interference. The fetal sources are isolated in vector $\hat{\mathbf{x}}_f = [\hat{x}_{f_1}, \hat{x}_{f_2}]^\dagger$, whereas the corresponding columns of the estimated mixing matrix are stored in matrix $\hat{M}_f = [\hat{\mathbf{m}}_{f_1}, \hat{\mathbf{m}}_{f_2}]$. The fetal heartbeat contributions to the recordings are then obtained via $\hat{\mathbf{y}}_f = \hat{M}_f\hat{\mathbf{x}}_f$. This procedure allows the estimation of FECG contributions to *all* leads [12]. However, only the abdominal signals are shown in Fig. 4 for the sake of a more meaningful comparison with the MRANC.

5. Discussion

Waveforms 1, 2, 3 and 5 of Fig. 3 show fairly clear fetal heartbeat signals by the MRANC. Waveform 4 is still corrupted by an important baseline wandering, presumably due to the mother's respiration, which hinders the observation of the fetal heart complexes in such electrode. Since there is hardly any of this wandering component present in the chest leads, it cannot be filtered and subtracted from the 4th abdominal electrode, where it appears. The performance of the MRANC method seems very dependent on the electrode placement, similarly as occurs with BSS based on second-order statistics (SOS) [5, 6]. The reference electrodes must be such that they contain signal components correlated with the interference in the primary electrodes.

All FECG contributions reconstructed by the BSS method appear cleaner from noise and residual MECG. For instance, the baseline wandering which corrupted the 4th signal obtained by the MRANC solution (Fig. 3) is now completely eliminated in Fig. 4, since it is found to be generated by an independent source of interference and hence it is extracted from the 4th recording as a separate noise signal.

For the application in clinical environments, on-line (or adaptive) processing is more convenient. Adaptive BSS methods (e.g., [9]) are shown to need longer

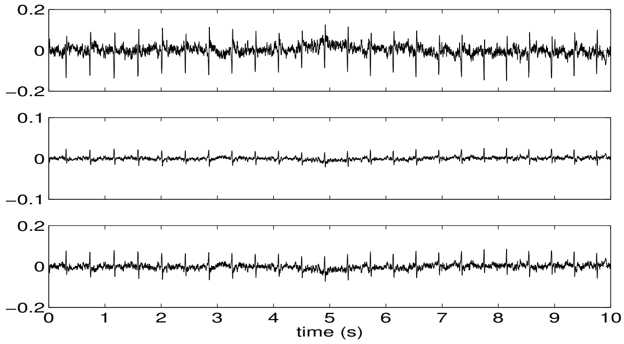

Figure 5. FECG contributions to electrodes 3, 4 and 5 of Fig. 1 obtained from only such three electrodes.

recordings to reach a satisfactory stable solution. This is connected with the larger sample sizes required to accurately estimate HOS. By contrast, in the MRANC only SOS are used, resulting in fast-converging, more stable adaptive implementations [11].

Besides the above considerations, a very strong point of BSS is its robustness with respect to the electrode placement and number. In further experiments FECG sources were clearly revealed by exploiting a few abdominal leads exclusively, with favourable results from up to only 3 electrodes. An an illustrative example, the fetal source estimated from signals 3, 4 and 5 of the recording of Fig. 1 yields the FECG contributions displayed in Fig. 5 (cf. last 3 plots of Figs. 3 and 4). The FECG extraction achieved from such smaller number of electrodes can still be considered as satisfactory. This robustness arises as an important major advantage of BSS techniques.

6. Conclusion

Compared to the classical MRANC method, HOS-based BSS shows a more robust, superior performance in the problem of FECG extraction from maternal cutaneous recordings. These initial results need to be substantiated with further patient data. Also, certain issues still remain to be investigated, such as the relationship between physiological sources of cardiac activity and the statistically-independent sources estimated by the signal separation methods. However, the obtained positive results could mean a step forward towards the implantation of BSS techniques as a generalized diagnostic tool in prenatal medicine.

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