FOETAL ECG SEPARATION

A. K. Nandi and V. Zarzoso†

Abstract. The extraction of the foetal electrocardiogram (FECG) from skin electrode signals recorded from a pregnant woman is a problem of concern to Signal Processing which accepts a model-based approach. Taking on board the bioelectrical phenomena which rule the cardiac activity and the propagation of heartbeat signals across the body, the FECG reconstruction may be modelled in the context of blind signal separation (BSS). Experimental results show the applicability of such BSS techniques to this biomedical problem.

1. Introduction

The function of the human heart is based upon the activity of a region called *sinoatrial (SA) node*. The SA node periodically generates electric pulses which are forwarded towards the four heart chambers, the *atria* and the *ventricles*, making them contract and expand accordingly. These contractions and expansions are associated to electric currents which propagate across the body, creating potential differences that can be measured from electrodes placed at specific points on the skin. The signals recorded through this procedure are known under the name of *electrocardiogram (ECG)*.

In the same manner the ECG can be obtained from an adult, it is often of interest to record the ECG from the foetus, specially in order to monitor their well-being during pregnancy. Several techniques exist to do so. Among them, *invasive* methods have proved the most accurate, but their major drawback is that they require access to the foetal scalp, and hence are only feasible during delivery. Consequently, *non-invasive* procedures must be employed if the *antepartum* foetal ECG (FECG) is to be obtained. These usually involve the recording of signals from skin electrodes located at different points of the mother's body. As a result, the electrodes output the wanted foetal heartbeat components buried under an additive mixture of maternal ECG (MECG) contributions and other disturbances which become important owing to the low amplitude range of the FECG signals. These other sources of interference are, mainly: maternal muscle activity (*electromyogram*) and respiration, mains coupling, and thermal noise from the electronic equipment (electrodes, amplifiers, etc.). Signal Processing techniques have thus to be applied in order to recover the desired FECG components from the corrupted cutaneous electrode recordings, that is, to perform FECG extraction.

In the present contribution, it is seen how a model-based approach proves very appropriate to this particular situation. Precisely speaking, this problem may be mathematically formulated from a *blind identification* standpoint. Hence, *Blind Source Separation (BSS)* techniques may be applied in this framework. The general rationale behind them is explained and their performance illustrated through a real multichannel ECG recording taken from a pregnant woman.

2. Some non-model-based solutions to the FECG problem

The ECG consists of successive *PQRST-complexes*. The frequency of repetition, which corresponds to the frequency of the electric pulses generated by the SA node, is called the *heart rate*. Given the evident observation that mother and child show different heartbeat rates, a first idea is to perform an optimal filtering in the frequency domain. However, there exists an overlap between mother's

†Signal Processing Division, Department of Electronic and Electrical Engineering, University of Strathclyde, Glasgow.

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and foetus' ECG spectra, which makes this solution not very promising. Moreover, the period of the heartbeat does not have a fixed value, but exhibits a random fluctuation mainly caused by respiration and the blood pressure and thermoregulatory control systems. This fluctuation is referred to as *heart rate variability (HRV)*. On the other hand, the coefficients of the optimum filter would depend on the patient, as well as on time, since the geometrical and electrical parameters of the body of a single patient are not constant (due, e.g., to foetal growth and movement). In addition, for medical diagnosis and treatment, it is crucial that unexpected ECG patterns can be detected and examined [LAT95]. All the above does not recommend the use of fixed filtering techniques.

Widrow and colleagues [WID75] suggest an adaptive multi-reference noise cancelling set-up for extracting the FECG contribution to an abdominal lead. This lead, which contains both maternal and foetal ECG components, acts as a primary input to the canceller. Several thoracic (chest) leads — containing mainly MECG components only — serve as reference inputs, and are adaptively filtered and subtracted from the primary input to produce the output signal. It turns out that adaptively varying the filter weights so that the mean-square error (the output power) is minimized, the MECG contribution at the output is considerably reduced and there remains an enhanced foetal heartbeat signal.

3. BSS model

A more efficient and rational approach to the FECG reconstruction problem comprises a previous examination of two different aspects, closely related to the biomedical application in hand: firstly, the nature of the generated signals, and secondly, the characteristics of the propagation from the bioelectric sources to the electrodes.

In the first place, the heart electrical activity has to be modelled. Burger and Van Milaan introduced the *lead-vector* concept [PLO69]: at a certain distance from the heart, its bioelectrical activity can be represented, to a first order approximation, by a three-dimensional dipole current fixed in position but variable in magnitude and orientation. This means that any MECG signal measured from the mother's body may be expressed as the superimposition of three orthogonal signals, the so-called *MECG sources*. The three-dimensional vector space spanned by the MECG sources is denoted as the *MECG subspace*. Accordingly, a *FECG subspace* can also be defined, spanned by the *FECG sources*, foetal counterparts of the MECG sources. However, it is claimed in [OOS89] that the dimension of the latter subspace is not necessarily equal to three, but it is actually subject to changes during the pregnancy period. One can assume that, in general, q source signals suffice to represent the activity of all internal bioelectric current sources. Then, at time instant t, a source signal vector $\mathbf{x}(t)$ can be defined as:

$$\mathbf{x}(t) = [x_1(t), \ldots, x_q(t)]^t \in \mathbb{R}^q,$$

where $x_i(t),\ i = 1, \ldots, q$, are the ECG sources. Nevertheless, what is actually measurable is the potential differences between electrode pairs placed on the body surface. If p of such measurements are taken, say $y_i(t),\ i = 1, \ldots, p$, they can be represented by a vector signal $\mathbf{y}(t)$:

$$\mathbf{y}(t) = [y_1(t), \ldots, y_p(t)]^t \in \mathbb{R}^p.$$

The second important issue to be considered is how the bioelectric sources generate the observed potential measurements, i.e., the propagation characteristics of the body from sources to electrodes. In the frequency range of interest (covering approximately between 0.5 Hz to 100 Hz) the body as a conductive medium behaves in a linear and resistive manner. Furthermore, the heart signals can be considered narrowband, compared to the propagation velocity, and so propagation delays are negligible. As a result, each measurement signal $y_i(t)$ may be expressed as a particular instantaneous linear combination of the q heart sources, plus some additive noise $n_i(t)$ which represents the other random perturbations mentioned in section 1:

$$\begin{array}{ccccccccc} y_1(t) & = & m_{11}\,x_1(t) & + & \cdots & + & m_{1q}\,x_q(t) & + & n_1(t) \\ \vdots & & \vdots & & \vdots & & \vdots & & \vdots \\ y_p(t) & = & m_{p1}\,x_1(t) & + & \cdots & + & m_{pq}\,x_q(t) & + & n_p(t) \end{array}$$

or using matrix notation:

$$\mathbf{y}(t) = M \cdot \mathbf{x}(t) + \mathbf{n}(t). \tag{1}$$

In the above equation, only $\mathbf{y}(t)$ is known. The matrix $M \in \mathbb{R}^{p \times q}$, containing the coefficients of the linear combinations, describes the propagation from sources to electrodes, and hence it is called *transfer matrix*. In fact, its element m_{ij} is the coefficient by which the jth source signal is present in the ith measurement. The transfer matrix is entirely determined by the geometry of the body, the electrode and source positions and the conductivity of the body tissues [CAL90], [VAN87]. The sources may be regarded as being statistically independent, due to the physical independence of the underlying bioelectrical phenomena. For analogous reasoning, the noise components, $n_i(t)$, $i = 1, \ldots, p$, are also assumed mutually independent, as well as independent from the source signals. As a conclusion, the separation of MECG and FECG can be formulated as a BSS problem: given the measurements $\mathbf{y}(t)$ in (1), find estimates of both the transfer matrix M and the sources $\mathbf{x}(t)$. This is a good example of an *inverse* problem: from the surface potentials, obtain the bioelectric sources and the body propagation characteristics.

On the other hand, let us consider the partitioning of $\mathbf{x}(t)$ into a block of maternal signals and a block of foetal signals, and the corresponding partitioning of the columns of M:

$$\mathbf{x}(t) = \begin{bmatrix} \mathbf{x_m}(t) \\ \mathbf{x_f}(t) \end{bmatrix}; \qquad M = [M_m \mid M_f].$$

Then the observations in $\mathbf{y}(t)$ may be expressed as the superimposition of maternal, foetal and noise contributions:

$$\mathbf{y}(t) = M_m \cdot \mathbf{x_m}(t) + M_f \cdot \mathbf{x_f}(t) + \mathbf{n}(t) = \mathbf{y_m}(t) + \mathbf{y_f}(t) + \mathbf{n}(t).$$

Therefore, the estimation of the FECG sources provides the FECG contribution to each recording free from MECG and other perturbations, simply by using the foetal sources $\mathbf{x_f}(t)$ and the corresponding columns, M_f, of the transfer matrix.

In short, on account of the above arguments, BSS techniques can be used to tackle the FECG extraction problem.

4. Methods for blind separation of sources

Most approaches to BSS exploit the statistical independence hypothesis of the source signals, along with the ability of the cumulants to measure the degree of such independence. Specifically, a set of random variables is said to be mutually independent if and only if all their cross-cumulants are null [BRI81]. The general procedure followed by BSS methods consists in seeking a linear transformation to be applied on the observations such that the cross-cumulants of the output signals vanish, thus yielding a set of mutually independent signals. Under certain conditions — at most one Gaussian signal among the sources [TON91] — those will be the desired source signals. From another standpoint, one could say that a kind of *spatial filtering* is carried out, since each source is recovered through a linear combination or weighted sum of the observed measurements [CAL90], [VAN87]. The particular methods differ in the way the weighting coefficients of this linear combination are determined although, basically, they can be split into two main groups: those which resort to second-order statistics and those which additionally take advantage of the higher-order statistical information contained in the available data. The methods in the first group simply perform a *Principal Component Analysis (PCA)* on the measurements, whereas those in the second one go further and carry out an *Independent Component Analysis (ICA)* of the inputs.

The PCA of a random vector [MAR79], [JOH88], looks for a linear transformation that provides uncorrelated components, i.e., with a diagonal-structure covariance matrix. This well-known statistical technique, based on the decomposition of the covariance matrix of the observed variables, may be accomplished in an efficient, robust and numerically reliable way by means of the Singular Value Decomposition (SVD) [CAL90], [COM94]. Nevertheless, it can be shown that second-order analysis is not always able to extract the source signals in a model like (1) leaving their waveforms undistorted, but there remains an indeterminacy in the form of an orthogonal matrix that this kind of methods cannot unveil.

For the part of the ICA methods, by contrast, the indeterminacy vanishes. The ICA of a random vector consists in searching for a linear transformation that yields independent components [COM94]. Note that the concept of (higher-order) statistical independence is stronger than that of uncorrelation, which only comprises second-order independence. The use of this extra higher-order information of the inputs allows the original source waveforms to be extracted. The ICA may actually be regarded as a refinement on the PCA results, which provides a remarkable improvement in the sources estimation.

For a thorough account of three of such BSS methods, refer to [BAC96] and [ZAR97].

5. Experiments

In order to illustrate the exposition above, a experiment on real ECG data is carried out. What follows can be found in more detail in [BAC96] and [ZAR97]. The 8-channel ECG recording obtained from a pregnant woman shown in figure 1 is inputted to two BSS methods, the PCA (via SVD) and the one depicted in [COM94], denoted here as the Higher-Order Eigenvalue Decomposition (ICA-HOEVD). Each recording has been sampled at a rate of 500 Hz during 10 seconds, and so is composed of 5000 samples. The first five signals correspond to abdominal electrodes, with little but still noticeable foetal complexes, whereas the last three were taken from the mother's thoracic region, almost completely free of any foetal heart contribution. The reason why thoracic electrodes are utilized, despite seeming pointless for the current application, is already explained in [VAN87] and it is also justified in the adaptive filtering solution given in [WID75]. Effectively, in order to remove the MECG from the abdominal recordings, it seems appropriate to obtain MECG interference signals as clean as possible so that they can be 'subtracted', after being properly weighted, from the abdominal signals without altering the existing FECG components. This point of view, in turn, permits to decouple the problem of determining electrode locations into two separate ones: (1) Thoracic electrodes are used to achieve MECG elimination, and (2) abdominal ones serve to improve the FECG-to-noise ratio, i.e., are employed for optimal FECG detection.

The source signals supplied by the two procedures are displayed in figures 2 and 3, respectively. The PCA only discloses two clear MECG signals (1st and 2nd waveforms), while the third one (4th signal) is extremely noisy. The 5th and 7th waveforms in figure 2 correspond to the foetal sources. The first one presents a low-frequency fluctuation, surely due to the maternal respiration. The ICA-HOEVD method remarkably improves these results, as expected in the light of theoretical considerations. Three clean maternal sources appear in the 1st, 2nd and 4th place in figure 3. Moreover, the low-frequency fluctuation disappears and now the two FECG source waveforms are recovered with great accuracy (5th and 7th positions).

6. Summary and conclusions

Taking into account the electric behaviour of the heart and the characteristics of the body as a conductive medium, the problem of detecting the FECG and suppressing the MECG and other interferences from recordings obtained through electrodes located on the mother's skin can be structured as a BSS model. As a consequence, BSS techniques can be used to cope with it. Apart from being simple, smart and intuitively appealing, this model proves, with the aid of practical experiments, its appropriateness for this specific biomedical application. In fact, the foetal heartbeat contributions to the recordings are reconstructed with an outstanding quality, from a set of original signals where the foetal complexes were hardly detectable to the naked eye. Although the experiments have involved batch processing — as opposed to adaptive processing — (that is, a whole matrix containing in its columns successive samples of the recordings is fed into the methods) procedures for adaptively performing blind separation of signals do exist and can be found in the literature. Those adaptive BSS methods could be useful in implementing real-time FECG extraction systems, such as those already outlined in [VAN87] and [CAL90]. This real-time realizations are most desirable, since they would allow on-line medical monitoring and diagnosis.

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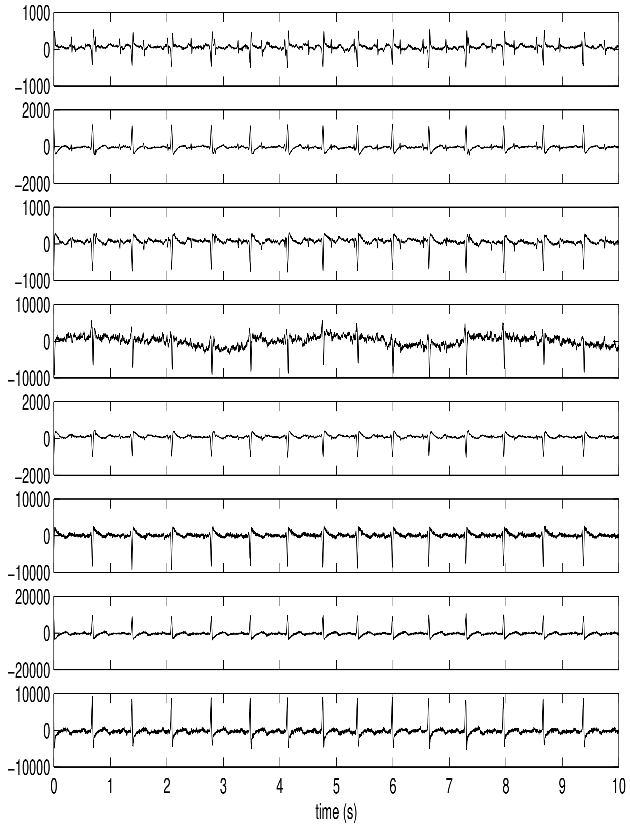

Figure 1: 8-channel electrocardiogram recording.

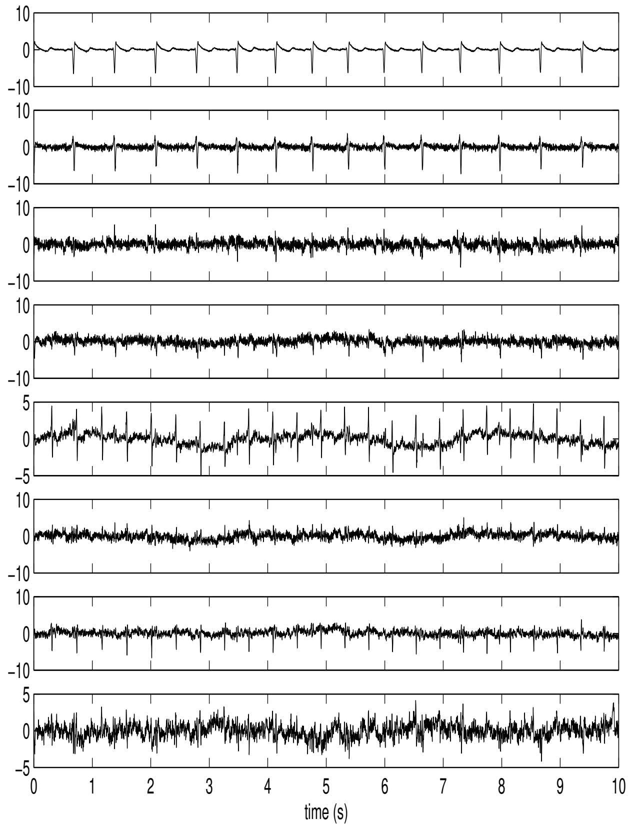

Figure 2: Source signals from the PCA method.

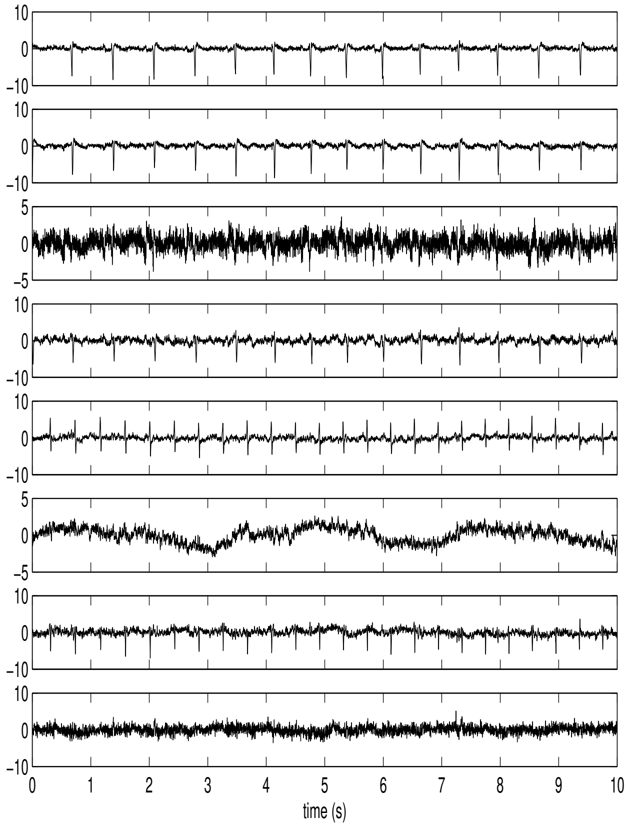

Figure 3: Source signals from the ICA-HOEVD method.