Extraction of Fetal Cardiac Signals from an Array of Maternal Abdominal Recordings

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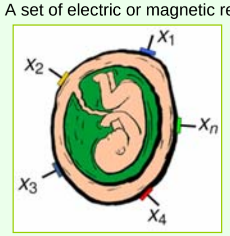
Abstract

Congenital heart defects are among the most common birth defects and the leading cause of birth defect-related deaths. Most cardiac defects have some manifestation in the morphology of cardiac electrical signals recorded by electrocardiography, and are believed to contain much more information as compared with conventional sonographic methods. Therefore, the noninvasive study of fetal cardiac signals can provide an effective means of monitoring the well-being of the fetal heart and may be used for the early detection of cardiac abnormalities.
In previous studies, various methods have been developed for the processing and extraction of fetal electrocardiogram (ECG) signals recorded from the maternal body surface. However, due to the low signal-to-noise ratio of these signals, the application of fetal electrocardiography has been limited to heartbeat analysis and invasive ECG recordings during labor.
In this research, the objective is to improve the signal processing aspects of fetal cardiography and to provide better insights of this problem, by developing new techniques for the modeling and filtering of fetal ECG signals recorded from an array of electrodes placed on the maternal abdomen. The basic idea behind the developed methods is to use a priori information about cardiac signals, such as their pseudo-periodic structure, to improve the performance of the currently existing techniques and to design novel filtering techniques that are customized for cardiac signals. Due to the overlap of the fetal signals and interferences/noises in different domains, the methods that use the information in only one of these domains do not usually succeed in extracting the fetal ECG. Therefore, we design methods that use the information from various domains, in order to improve the quality of the extracted signals.
Theoretically, the proposed methods are combinations of morphological models of the ECG, *ad hoc* Bayesian filtering techniques based on estimation theory, and special classes of spatial filters adapted from the blind and semi-blind source separation context. It is shown that due to the generality of the proposed methods, the same procedures are also applicable to multichannel adult ECG recordings and can be used in real-time cardiac monitoring systems. Moreover, the developed methods are based on the cardiac signal morphology without going into the details of volume conduction theory and the conductivities of the propagation media. Hence, the same methods are applicable to other cardiac monitoring modalities such as the magnetocardiogram (MCG), which are morphologically similar to the ECG. We specifically present a case study on the extraction of twin fetal MCG signals.
We also present an advanced deflation technique, which is able to separate subspaces of desired signals from degenerate mixtures of signal and noise. This idea has found various applications in other contexts.

Problem Definition

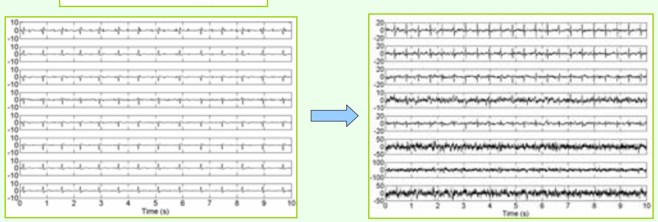
Objective: The noninvasive extraction of fetal cardiac signals from an array of electrodes recorded from the abdomen of a pregnant woman using advanced signal processing techniques

A set of electric or magnetic recordings



$$\mathbf{x}(t) = \begin{bmatrix} x_1(t) \\ x_2(t) \\ \vdots \\ x_n(t) \end{bmatrix} \Rightarrow \mathbf{y}(t) = \begin{bmatrix} y_1(t) \\ y_2(t) \\ \vdots \\ y_m(t) \end{bmatrix}$$

Noisy observation signals | Processed signals

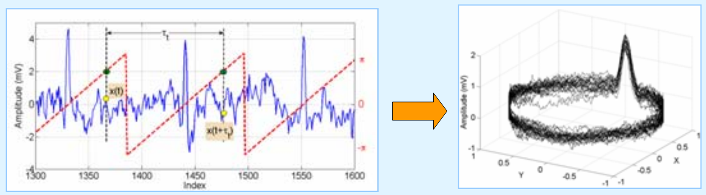


Method 1: Periodic Component Analysis (PiCA)

PiCA is a general algorithm for extracting pseudo-periodic components from multichannel recordings

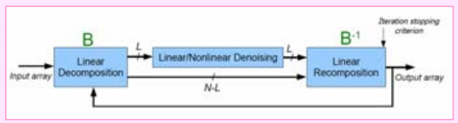
Algorithm:

- Detect the R-peaks of the ECG of interest (*a priori* information)
- Calculate the ECG phase signal $\theta(t)$
- Calculate the time-varying lag $\tau_t = min\{\tau|\phi(t+\tau) = \phi(t), \tau > 0\}$
- Calculate $C_x = E_t\{\mathbf{x}(t)\mathbf{x}(t)^T\}$ and $\tilde{C}_x = E_t\{\mathbf{x}(t+\tau_t)\mathbf{x}(t)^T\}$
- $B \leftarrow GEVD(C_x, \tilde{C}_x)$



Method 2: Subspace Decomposition By Deflation

This is a general method for the decomposition of signals within coplanar (intersecting) planes. It is a combination of linear and nonlinear methods; but does not have the limitations and drawbacks of linear decomposition methods.

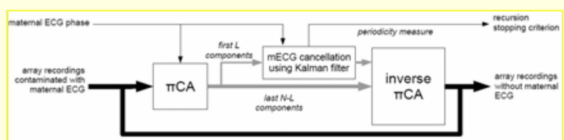


Subspace Decomposition Algorithm:

$\mathbf{x}^{(0)}(t) = \mathbf{x}(t)$, $k = 0$
repeat
  Calculate $C_{\mathbf{x}}^{(k)}$, the covariance matrix of $\mathbf{x}^{(k)}(t)$
  Calculate $Q_{\mathbf{x}}^{(k)}$, the matrix containing the desired statistics of $\mathbf{x}^{(k)}(t)$
  $W^{(k)} \leftarrow \mathrm{GEVD}(Q_{\mathbf{x}}^{(k)}, C_{\mathbf{x}}^{(k)})^T$
  $A^{(k)} \doteq [\mathbf{a}_1^{(k)}, \ldots, \mathbf{a}_N^{(k)}] \leftarrow W^{(k)^{-1}}$
  $\mathbf{y}^{(k)}(t) \leftarrow W^{(k)}\mathbf{x}^{(k)}(t)$
  $\mathbf{s}^{(k)}(t) \doteq [s_1^{(k)}(t), \ldots, s_L^{(k)}(t)]^T \leftarrow \mathbf{G}(\mathbf{y}^{(k)}(t))$
  $\mathbf{x}^{(k+1)}(t) \leftarrow \mathbf{x}^{(k)}(t) - \sum_{j=1}^{L} \mathbf{a}_j^{(k)} s_j^{(k)}(t)$
  $c \leftarrow \mathscr{P}(\mathbf{x}^{(k+1)}(t))$
  $k \leftarrow k + 1$
until $c \leqslant th$

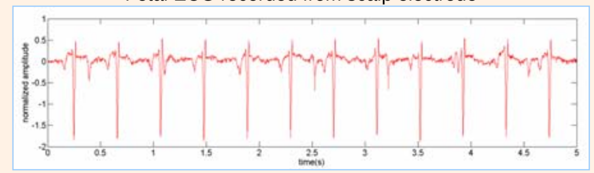
The proposed iterative technique is highly generic, with various applications in different contexts.
This algorithm has been patented in the U.S. and is currently used in the signal processing core of MindChild Medical, Inc. fetal monitoring system, for the extraction of fetal cardiac signals from maternal abdominal recordings

Application in Maternal ECG Cancellation

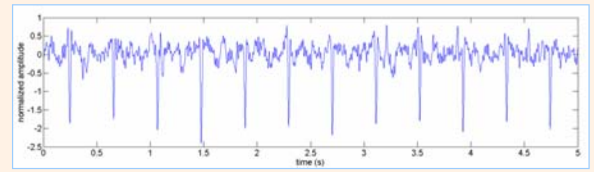


Example 1: fECG extracted from abdominal sensors vs. fetal scalp electrode

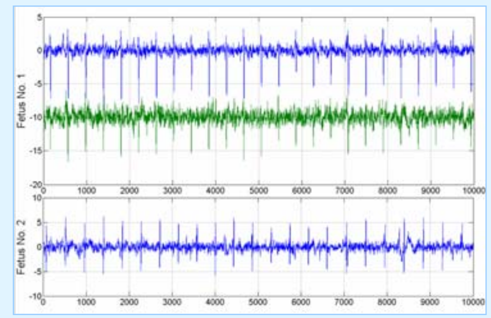
Fetal ECG recorded from scalp electrode



Extracted Fetal ECG



Example 2: Extraction of fetal MCG of twins



Conclusions

The extraction of fetal ECG and MCG signals is highly simplified using the proposed technique. The method has recently found industrial applications in real-time fetal ECG monitoring systems.

References

R. Sameni, M.B. Shamsollahi, C. Jutten, and G.D. Clifford, **Extraction of Fetal Cardiac Signals**, *U.S. Patent*, Filed: November 21, 2008, Serial Number: 61/116,870

R. Sameni, C. Jutten, and M. B. Shamsollahi, **A Deflation Procedure for Subspace Decomposition**, *IEEE Transactions on Signal Processing*, 2009 [accepted, in press]

R. Sameni, C. Jutten, and M.B Shamsollahi, **Multichannel Electrocardiogram Decomposition using Periodic Component Analysis**, *IEEE Transactions on Biomedical Engineering*, Vol. 55, No. 8, pp. 1935-1940, Aug. 2008

R. Sameni, **Noninvasive Extraction and Processing of Fetal Cardiac Signals from an Array of Maternal Abdominal Recordings**, *PhD Thesis* , Sharif University of Technology - GIPSA-LAB, INPG, 2005-2008

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