Cancellation of the Maternal and Extraction of the Fetal ECG in Noninvasive Recordings

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Abstract

No signal processing technique has been able to reliably deliver an undistorted fetal electrocardiographic (fECG) signal from electrodes placed on the maternal abdomen because of the low signal-to-noise ratio of the fECG recorded from the maternal body surface, resulting in increased rates of Caesarean deliveries of healthy infants. In an attempt to solve the problem a Physionet/Computing in Cardiology announced the 2013 Challenge: Noninvasive fetal ECG.

We are suggesting a method for cancellation of the maternal ECG consisting of: maternal QRS detection, heart rate dependant P-QRS-T interval selection, location of the fiducial points inside this interval for best matching by cross correlation, superimposition of the intervals, calculation of the mean signal of the P-QRS-T interval, and sequential subtraction of the mean signal from the whole fECG recording. A combined lead of all the 4 channels was synthesized and fetal QRS detection was performed on it.

All 100 recordings of test set B were processed, the times of occurrence of the fetal QRSs were recorded and sent as results to the Organizers of the Challenge. The calculated average scores are: 285.132 for Events 1 and 4: Fetal heart rate measurement; 19.962 for Events 2 and 5: Fetal RR interval measurement

1. Introduction

Heart defects are among the most common birth defects and are the leading cause of birth defect-related deaths [1]. The defects originate in early weeks of pregnancy when the heart is forming and undergoing a considerable amount of growth.

Although the advent of fetal heart rate monitoring was introduced into clinical practice in the 1970s no signal processing technique has been able to reliably deliver an undistorted fetal electrocardiographic (fECG) signal from electrodes placed on the maternal abdomen because of the low signal-to-noise ratio of the fECG recorded from the maternal body surface [2]. The application of fECG has therefore been almost completely limited to heart-beat analysis and invasive ECG recordings, e.g., by placing an electrode on the fetal scalp during labour. Although this is currently the only way to reliably measure fECG waveform, it can be accomplished only under limited clinical circumstances, presenting a risk to the fetus' safety.

No current standards exist for electrode location in noninvasive fECG, and usually the electrodes are placed in concentric circles on the abdomen, covering all available angles.

A review of Sameni and Clifford [2] highlights several fECG processing methods:

Adaptive Filtering: These methods consist of training an adaptive filter for removing the maternal ECG using either one or several maternal reference channels [3], or directly training the filter for extracting the fECG [4,5].

Linear Decomposition: In this method, the signals are decomposed into different components by using suitable basis functions that are somehow in coherence with the time, frequency, or scale characteristics of the fetal components. Wavelet decomposition [6] and matching pursuits [7] are among these methods.

Nonlinear Decomposition: A limitation of the linear decomposition is the fact that fECG and other interferences and noises are not always ‘linearly separable’. One solution is to use nonlinear transforms for separating the signal and noise parts of the signal [8,9]. The nonlinear transforms require some prior information about the desired and undesired parts of the signal.

Sameni and Clifford [2] are comparing the processing methods on whether they are single- or multi-channel, real time implementation (yes/no), overall performance (low, medium, high), signal-to-noise ratio improvement (low, medium, high), operator action (yes/no), implementation complexity (simple, medium, complex). The authors conclude that: Each method has its own benefits and limitations and is applicable for specific scenarios.

2. Methods

The data for the challenge consists of one-minute fECGs, recorded at a sampling frequency of 1000 Hz. Each recording includes four noninvasive abdominal signals. A learning set (called 'set A') of 75 fECG recordings, as well as the reference annotations for them were provided to all the participants of the Challenge [10]. Another test set (called 'set B') of 100 fECG recordings for evaluation of the challenge entries in Event 4 (Fetal heart rate measurement) and Event 5 (Fetal RR interval measurement) were provided.

We are suggesting a method for cancellation of the maternal ECG consisting of: maternal QRS detection, heart rate dependant P-QRS-T interval selection, location of the fiducial points inside this interval for best matching by cross correlation, superimposition of the intervals, calculation of the mean signal of the P-QRS-T interval, and sequential subtraction of the mean signal from the whole fECG recording. A combined lead of all the 4 channels was synthesized and fetal QRS detection was performed on it.

Filtering of mains interference and electromyographic (EMG) noise was not used, because the fetal ECG (fECG) has very low amplitude and its frequency range is totally overlapping with the range of the noise

2.1. Maternal QRS detection

The adaptive QRS detection method of Christov [11] was used to detect the maternal QRSs. Two leads of the highest QRSs magnitude chosen from all the four leads were used as inputs of the algorithm. Just few false detections, marking a fetal as a maternal QRS were observed.

2.2. Fiducial points' location

Fiducial points' location was needed because the used QRS detection algorithm triggers at arbitrary moment inside the QRS.

The average maternal heart rate was obtained and the length of the P-QRS-T interval was calculated in accordance to it. Fiducial points for best matching of successive P-QRS-T intervals were achieved by cross correlation.

2.3. Mean P-QRS-T interval

Mean maternal signal in the P-QRS-T interval is calculated taking into account the fiducial points. Superimposition of all P-QRS-T intervals of a certain lead and the calculated mean signal are shown in Figure 1.

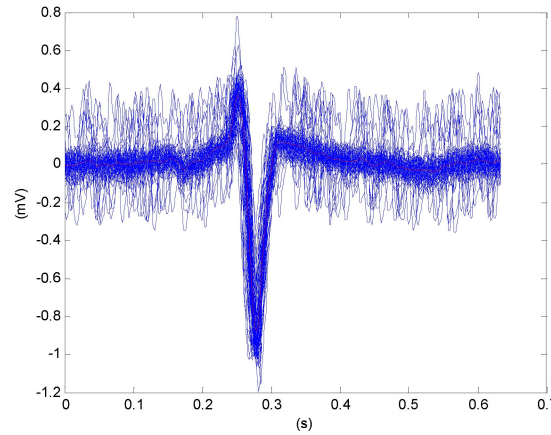

Figure 1. Superimposition of all P-QRS-T intervals (blue lines) and calculation of the mean signal (red line).

2.4. Subtraction of the mean signal

Subtraction of the mean maternal signal from the whole ECG recording is shown in Figure 2. Analysis showed that the result of the subtraction is negatively influenced by the presence of the smallest available drift. For that reason drift suppression with a cutoff frequency of 4 Hz (highly above the cutoff of 0.64 Hz, recommended for the diagnostic electrocardiograph) is performed. A high-pass recursive filter [12] has been used.

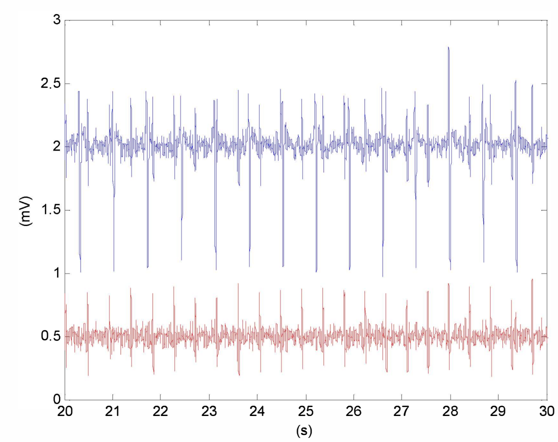

Figure 2. Subtraction of the mean maternal signal of Figure 1 from the whole ECG recording.

2.5. Fetal QRS detection

Two modifications of the adaptive method of Christov [4] were made in order to detect the fetal QRS:

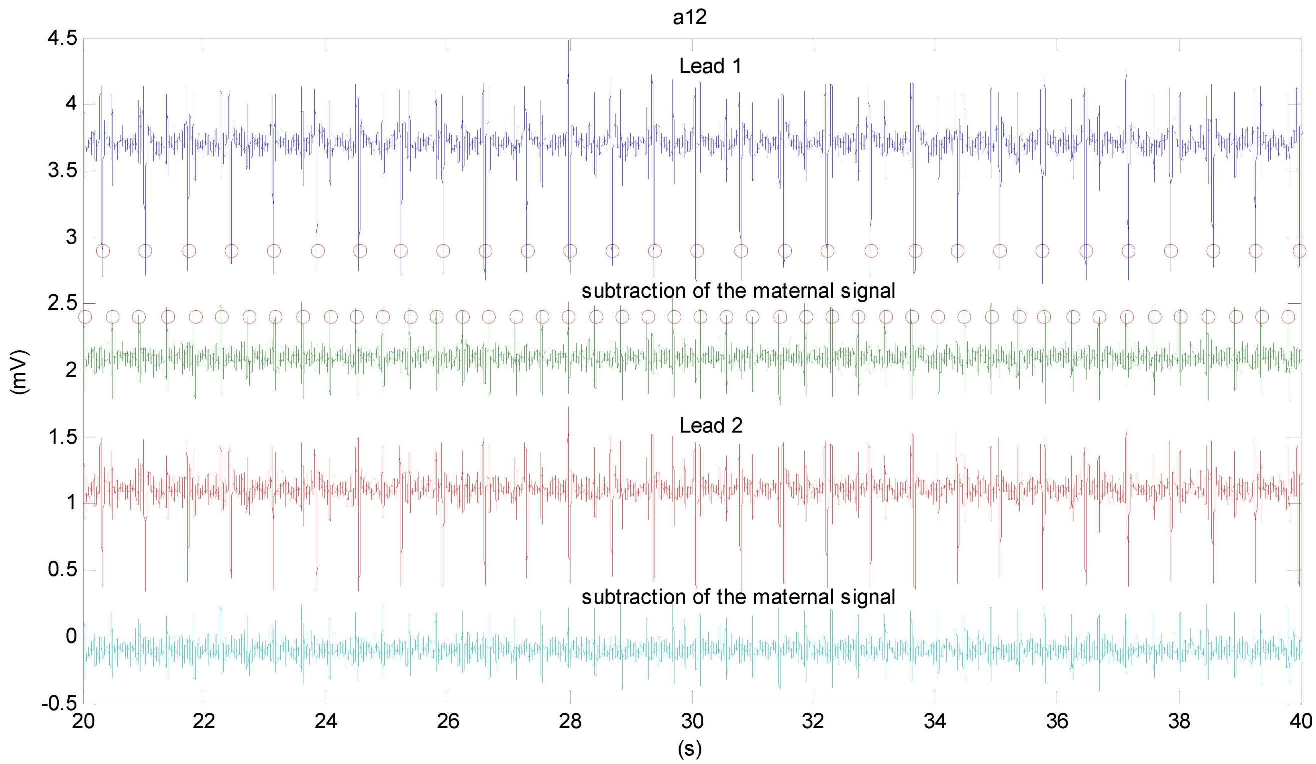

Figure 3. Illustration of the method for cancellation of the maternal and extraction of the fetal ECG
First trace – Lead 1 and maternal QRS detection; Second trace – Lead 1 after subtraction of the maternal signal and fetal QRS detection; Third trace – Lead 2; Fourth trace – Lead 2 after subtraction of the maternal signal;

- the hypothetical heart rate was tuned to 120-180 beats per minute;
- the 'complex lead' on which the QRS detection is performed, was synthesized of all the four fECG leads available by the Challenge database.

The whole method for cancellation of the maternal and extraction of the fetal ECG is illustrated in Figure 3. Although the algorithm is working with all the four leads, just 2 of the leads are presented in the Figure for clarity. The maternal QRS detection is shown on Lead1 (first trace. The fetal QRS detection is shown on the subtracted signal (second trace).

3. Results

All 100 recordings of test set B were processed, the times of occurrence of the fetal QRSs were recorded and sent as results to the Organizers of the Challenge. The calculated average scores are:

Events 1/4, Fetal heart rate measurement: 285.132;

Events 2/5, Fetal RR interval measurement:19.962.

4. Discussion

An essential component for evaluation of any fECG analysis algorithm is a representative and high quality database [2]. Bad signal quality is the limiting factor in the fECG analysis and the clinicians should know that there is no magic software that will solve the problem in this case.

The study of all 100 recordings in test set B shows:

- 25 cases either have no ECG (Figure 4) or the maternal QRS is very low - less than 0.1 mV (Figure 5);
- 5 cases are with very low signal-to-noise ratio (Figure 6);
- fetal QRSs can be visually observed in just a few recordings;
- in 28 cases the 4 leads are obtained by copy-paste of one and the same lead (see Figure 5), which reduces the information that would have been obtained from 4 independent leads;
- At least 5 cases are recorded with a drastic change of the amplitude scaling, which dooms to failure the possible use of amplitude criteria.

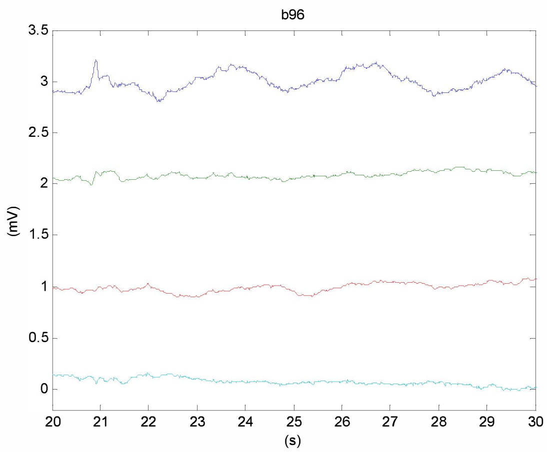

Figure 4. Example of recordings with no ECG

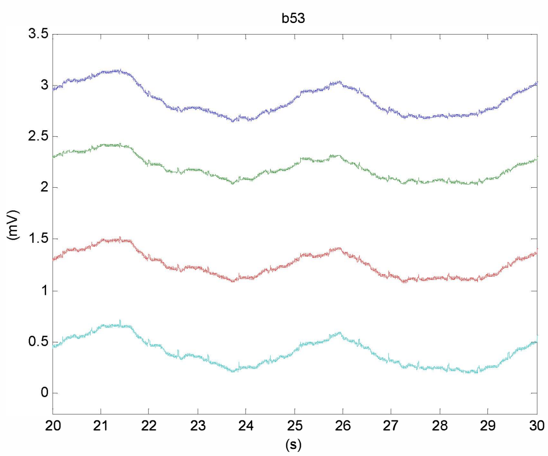

Figure 5. Example of recordings with very low maternal QRS of less than 0.1 mV.

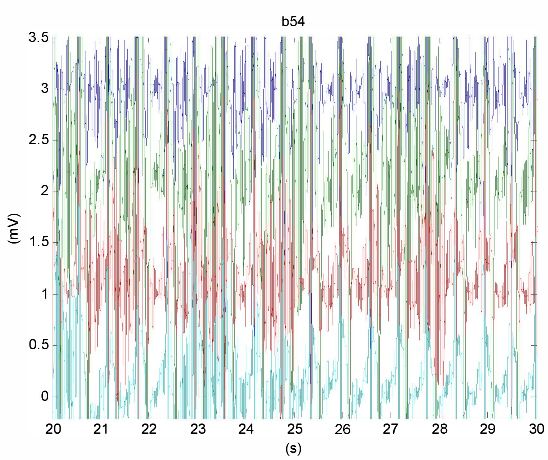

Figure 6. Example of very low signal-to-noise ratio

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