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Combined method for fetal electrocardiogram extraction from non-invasive abdominal recordings*

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Abstract— **Abdominal electrocardiogram (AECG) recording is a non-invasive method to assess fetal well-being during both pregnancy and delivery. However, AECG recording is contaminated by a series of physiological interferences which make difficult the extraction of morphological and temporal parameters of fetal ECG from the raw signals. In this work, it is proposed a combined method to extract the fetal ECG from AECG recording by removing the interferences on a cascade structure using a priori information about the signals nature. In this work, a total of 54 multichannel AECG recordings taken from 21 to 40 weeks of gestation were enrolled. Experimental results show that the proposed method outperforms conventional independent component analysis, and provides fetal heart rate detection in 80% of the cases. In addition it also permits to obtain fetal ECG morphology from AECG recordings.**

I. Introduction

Monitoring the fetal cardiac activity can provide important information to obstetricians for the assessment of the fetal well-being [1]. Doppler ultrasound is now routinely used for the measurement of the fetal heart rate during pregnancy and delivery [2]. Nevertheless this technique may require intermittent repositioning of the transducer [3] and the fetal heart rate is the unique parameter obtained by Doppler ultrasound. Whereas the morphological and temporal parameters of fetal ECG during gestation can provide additional information about the fetal well-being. In fact, changes in parameters such as the PR and PQ interval, the width of the QRS complex, and changes in the P wave, the T wave and ST segment have been associated with the level of fetal oxygenation [4]. The fetal electrocardiogram (FECG) can be obtained by applying an electrode on the fetal scalp. However, this technique is highly invasive and it is only possible during labour. In contrast, abdominal electrocardiogram (AECG) recordings provide a non-invasive diagnostic tool to assess fetal well-being during both pregnancy and delivery. Nevertheless, AECG recording is contaminated by a series of physiological interferences such as baseline drift, EMG, maternal ECG and motion artefacts [5].

Numerous signal processing techniques, such as adaptive filtering, template subtraction, wavelet transform and independent component analysis (ICA), have been widely used to detect the FECG in abdominal recordings [6]. The three former techniques focus on the removal of MECG from AECG recording. The presence of other significant interference signals in AECG recordings may reduce the performance of these techniques. In contrast, ICA has been shown to achieve promising results for FECG detection from 12-channels AECG recording on a large database of records [7]. Other authors sustain that a better performance of FECG extraction can be obtained when using the cascade of an event synchronous canceller and ICA [8], or PCA [9]. It should be noted that a large number of channels (12-13 channels) were available in these studies. When few channels are available, the ability of ICA to extract fetal cardiac activity is still to be proven. The aim of this work is to extract FECG from AECG recording when few channels (3-4) are available.

II. Materials and Methods

A. DATABASE

A total of 54 multichannel AECG recordings taken between 21 to 40 weeks of singleton pregnancy were enrolled in this study. All these recordings were available in physionet [10]. For each recording, 3 or 4 abdominal signals were obtained using Ag/AgCl electrodes placed on the mother's abdomen. Electrode positioning was varied in order to improve SNR. Two thoracic maternal ECG signals were simultaneously recorded. All these signals were bandpass filtered (0.01 Hz-100 Hz) and acquired with a sampling frequency at 1 kHz.

B. METHODS

Firstly a high pass filter with cut-off frequency at 1 Hz was applied to AECG recording in order to attenuate low-frequency components and a notch filter was designed for power-line interference removal. Then the preprocessed AECG signals were analysed using a combined method which consisted of the detection of FECG after the application of a cascade structure in order to remove the interference signals step by step. Each stage uses a priori information about the interference signal and/or the signal of interest.

Figure 1 shows the implemented cascade structure. Firstly maternal ECG (MECG) was removed by means of an event synchronous canceller (ESC) using the simultaneously

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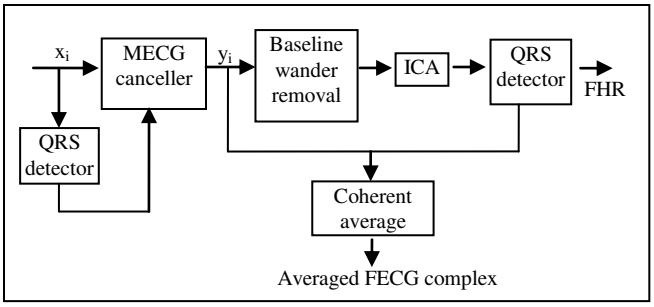

Figure 1: Block scheme of the proposed method for ECG detection.

recorded thoracic signals as reference signal. To this end, Pan and Tompkins algorithm was used for detecting maternal R-wave in one of the acquired thoracic signals. Then it was calculated the average of data sweeps (μ) of each AECG channel which were time-locked with the R-wave of MECG and extended from 250 ms prior to the R-wave to 450 ms after it. In order to correct the mismatch between the average and each individual beat caused by the time-varying morphology of the MECG, the averaged MECG complex is scaled with a constant (a) for each beat. The scaling is based on the search for the least-mean square error (e) between individual MECG complex (m) and the averaged MECG complex (μ), i.e., $e^2=\min\|\mu \cdot a-m\|^2$. Then the resulting scaled MECG complex estimate of each AECG channel is subtracted from its corresponding AECG signal. This method is similar to the MECG canceller proposed by Martens *et al* [9]. The main difference is that in this work the scaling procedure was performed considering the MECG complex as a whole, rather than scaling the P wave, the QRS complex and the T wave separately as proposed by Martens.

After the removal of MECG from AECG recordings, the resulting signals still contain other interferences such as baseline wander. Instead of using a high pass filter with a cut-off frequency that has to be decided subjectively, in this work empirical mode decomposition (EMD) was used for baseline wander removal. EMD is a general data analysis technique that consists of expanding a complex signal into a finite number of oscillatory functions known as intrinsic mode functions (IMF). IMFs can be interpreted as adaptive base functions extracted directly from the original signal, and represent the dynamic process hidden within the original signal and usually give a physical interpretation of the underlying process [11]. After the application of the EMD algorithm, each AECG channel $y_i[k]$ can be expressed as a linear combination of a series of IMFs:

$$y_i[k] = \sum_{j=1}^{N_i} IMF_{ij}[k] + r_{iN_i}[k] \quad (1)$$

Where IMF_{ij} is the j component after decomposing $y_i[k]$ and $r_{iN_i}[k]$ is the residual signal of the decomposition process.

The reconstruction process of the EMD algorithm is performed by adding fast oscillations up to slow oscillations [12]. Then the reconstructed signal can be specifically written as follows:

$$\hat{y}_i[k] = \sum_{j=1}^{K_i} IMF_{ij}[k] \quad (2)$$

Where $K_i<N_i$. In this work, the IMFs whose energy around the dominant frequency is greater than 50% of the IMF total energy, were considered to be associated to baseline wander and they were not taken into account in the reconstruction process (eq. (2)).

Subsequently, ICA was employed for the separation of fetal ECG and the remaining interferences embedded in the processed AECG recordings ($\hat{y}_i[k]$) [13]. After the visual identification of the the independent component (IC) that contains the fetal ECG signal, a Pan and Tompkins based QRS detection algorithm was used for detecting R wave. In order to further enhance the QRS complexes in fetal ECG signal, a method based on finding the maxima of the cross correlation of the signal with a QRS template was used [9]. Finally, after the identification of the QRS complexes, the fetal heart rate and the average FECG complex for each channel were calculated over 60 s of signal [7]. In this case it was performed the average of data sweeps extended from 150 ms prior to the fetal R-wave to 225 ms after it.

III. Results and Discussion

Figure 2 shows 10 s of four AECG (traces b-e) at 38 weeks of gestation simultaneously recorded with one thoracic ECG signal (trace a) after signal preprocessing. It can hardly be seen the presence of fetal ECG embedded in the strong MECG interference (an order of magnitude larger) in the four AECG recordings. MECG interference in the AECG recordings is time-locked with thoracic ECG signal, and its amplitude depends on the distance and angle of the electrode with respect to the mother's heart.

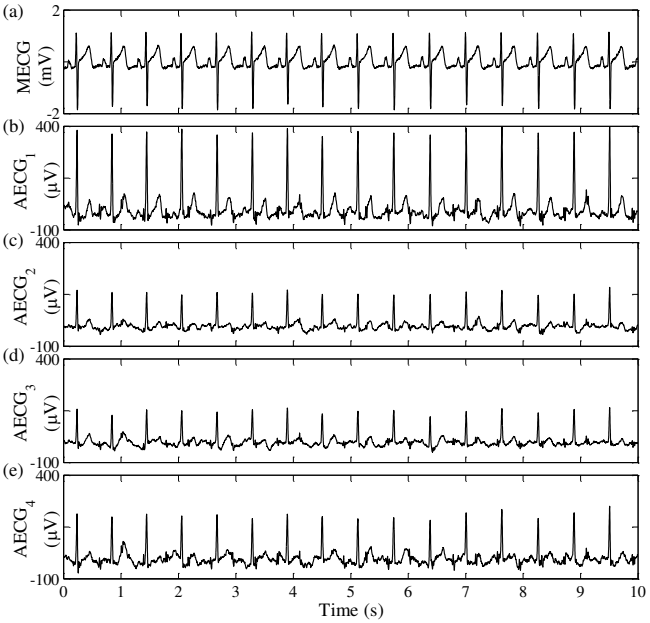

Figure 2: 10 s of AECG at 38 weeks of gestation recorded simultaneously with MECG after signal preprocessing. (a) MECG. (b)-(e) AECG.

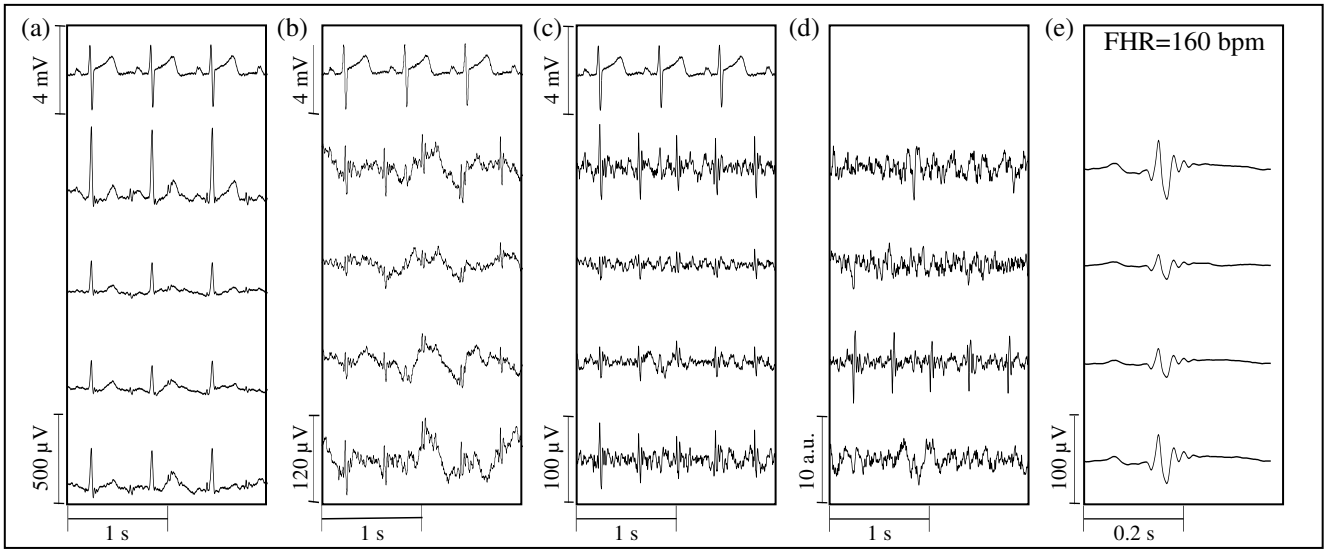

Figure 3: Combined method applied to the signals shown in Figure 2. (a) Maternal ECG (top trace) simultaneously recorded with 4 monopolar abdominal signal (bottom traces). (b) Signals after MECG canceller. (c) Signals after the removal of the baseline wander using EMD algorithm. (d) ICs after ICA analysis, the third trace contains most fetal cardiac activity. (e) Averaged FECG complexes extracted from each channel using coherent averaging method.

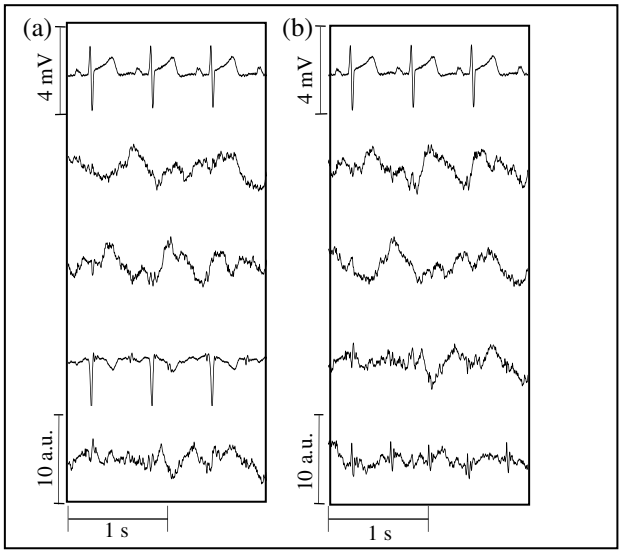

Figure 4: Comparison of the combined method with ICA analysis. (a) Results of ICA algorithm applied to the preprocessed signal (see figure 3a) (2 s). (b) Results of ICA algorithm applied to the signal after MECG canceller (2 s).

Figure 3 shows, step by step, the results of the fetal ECG extraction procedure of the signals shown in figure 2 using the proposed combined method. It can be seen that the ESC method can effectively cancel the MECG interference in AECG recordings (Fig.3b), preserving the target signal even when the MECG interference overlapped the FECG (first beat, around 0.4 s) In the same manner that occurs in maternal ECG, the FECG amplitude and morphology is time varying and also depends on the distance and angle of surface electrodes with respect to the fetal heart, specifically, the FECG amplitude in channels 1 and 4 is larger than that of channels 2 and 3. In addition to the FECG, it can also be observed the strong presence of the baseline wander in these signals (Fig. 3b). Figure 3c shows the signals after reducing the baseline wander using the EMD method, which are subsequently analysed by the ICA algorithm. The resulting ICs of the ICA algorithm are shown in figure 3d. In these traces, it can be seen that the third IC corresponds to fetal cardiac activity, and the other signal sources may be associated to background noises and remaining interferences. The fetal heart rate of 160 bpm was obtained using the QRS detection algorithm on this third IC. The averaged FECG complex over 60 s extracted from each channel is shown in figure 3e. In these traces it can be clearly seen the fetal P wave and QRS complex, while the T wave is of very small amplitude. These results agree with others authors who manifest the difficulties of extracting the fetal T wave from AECG recording due to its small amplitude, in spite of the clinical importance of the ST segment [7].

For further validation of the proposed method, it was compared to the straight application of ICA algorithm to the preprocessed signals shown in figure 2. The resulting ICs are shown in figure 4a. In these traces, it can be seen that the straight ICA analysis does not permit the separation of MECG and FECG embedded in original AECG recordings. As can be appreciated in this figure, the ICA algorithm was only able to concentrate the MECG and FECG mixed together in the third output. This finding agrees with other authors who reported that the ICA does not allow extraction of the independent source signals that can be physically interpreted when few channels are available, but only extracts the outputs signals that are as independent as possible [14]. On the other hand, the ICA algorithm was also applied to the signals after cancelling MECG interference using ESC method shown in figure 3b. The resulting ICs are shown in figure 4b. In this case, it can be seen that FECG is

TABLE I. FHR DETECTION SUCCESS RATE AND RELIABILITY OF THE COMBINED METHOD.

Week of gestation	Number of cases	Success rate
21-26	21	20
27-32	11	4
33-36	8	5
37++	14	14
Total	54	43

concentrated in the fourth output signal. This finding agrees with other authors who defend that the use of a cascade structure of ESC and ICA outperforms the simple ICA method even when 12-channels of AECG recording were available [8]. However, there is still a noticeable baseline wander embedded in the target signal (figure 4b, bottom trace). The comparison of the figure 4b and figure 3d suggests that the use of the EMD method prior to ICA analysis also outperforms the FECG extracted from AECG recordings. This can be of great importance when few recording channels are available.

Table I shows the FHR detection success rate and reliability of the proposed combined method. For a total of 54 AECG recording sessions analysed. The FECG complex was successfully extracted from 43 subjects, leading to a success rate of 80%. Moreover, the combined method is highly reliable for FECG extraction from AECG recorded at early stage of pregnancy (22-27 weeks of gestation) and also at the last stage of pregnancy (after 37 weeks of gestation). However, the success rate on recordings acquired at 27-32 weeks of gestation is low. This result agrees with other authors who reported the difficulties in obtaining FECG at mid-trimester (28-32 weeks of gestation) [7,9]. The low success rate during this period may be due to the decreased FECG amplitude which may be misled with background muscular noise from maternal abdomen. The fact of this decreased FECG amplitude is associated to the presence of vernix caseosa over the fetal skin, which is a fatty and isolating layer that appears around 28 weeks of gestation. This problem is partially overcomed at later gestations due to the increasing of fetal size and cardiac mass [7,9].

Due to the small amplitude of the non-invasive FECG, the FECG extraction from AECG recording is problematic. The results showed that the combined method proposed in this study can be used over a wide gestational range even when few channels are available (3-4 channels). We believe that using additional channels of AECG recordings will improve the ability of ICA algorithm to discriminate fetal cardiac activity from the background noise and other interferences such as motion artifacts, and therefore enhance the detectability of the FECG in AECG signals. In this way, the electrode repositioning in order to improve signal to noise ratio, which is a time consuming procedure, may not be necessary anymore. Nevertheless, the algorithm may need to be simplified to be used in on-line applications. On the other hand, the low success rate of recordings at 27-32 weeks of gestation should still be enhanced by improving the instrumentation devices and signal processing.

I. CONCLUSION

Experimental results show that fetal ECG can be extracted from non-invasive abdominal recordings using the proposed combined method with a success rate of 80%, even when only 3-4 AECG recording channels are available. This can be a very helpful tool which may enhance the potential clinical use of this non-invasive technique for monitoring fetal well-being.

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