Fetal Heart Rate Extraction from Composite Maternal ECG Using Complex Continuous Wavelet Transform

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Abstract

Fetal heart rate extraction from the abdominal ECG is of great importance due to the information that carries in assessing appropriately the fetus well-being during pregnancy. In this work a novel automated method is presented for the detection of the QRS complexes of the fetus cardiac activity using multi-channel maternal ECG recordings. No accessory preprocessing step for noise filtering is required. The method is based on the complex continuous wavelet transform and modulus maxima theory. The proposed method was validated using real signals, recorded at different weeks of gestation, covering most of the pregnancy period. The system performs well, since almost all fetal beats are detected (accuracy: 99.5%).

1. Introduction

The recording of fetal electrocardiogram (FECG) is a simple and noninvasive method for monitoring the electrical activity of the fetus heart (Fig. 1). Like the standard ECG, which reflects cardiac and metabolic activity, FECG is potentially a sensitive indicator of fetal health state. A common situation in ECG signal acquisition is the presence of noise, which deteriorates the signal's quality decreasing the signal-to-noise ratio (SNR). The sources of interference when acquiring the abdominal signals are: the maternal ECG, the myographic noise, the powerline interference, the fluctuation of the baseline and factors related to the gestation week. More specifically, the maternal influence in the composite signal has two main characteristics: (i) its spectra overlaps with that of the fetus and (ii) its energy is estimated to be more than 75% of the total signal's energy. Moreover, the abdominal FECG signal is characterized by a poor SNR, while its shape depends on the position of the electrodes, as well as on the gestational week. The fact that there is no standard electrode positioning for optimizing acquisition makes the problem of automated fetal heart rate extraction (FHR) more complex.

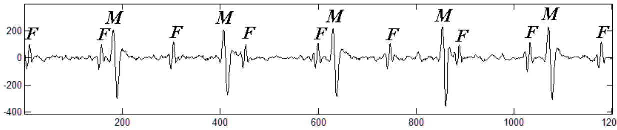

Fig. 1: Abdominal ECG recording, F: Fetal influence, M: Maternal influence.

Various research efforts have been devoted in FECG detection and FHR extraction. The most recent ones include algorithms based on singular value decomposition [1,2], auto and cross-correlation techniques [3], adaptive filtering [4,5], orthogonal basis functions [6], fractals [7], FIR neural networks [8], IIR adaptive filtering combined with genetic algorithms [9], fuzzy logic [10], frequency tracking [11] and real-time signal processing [12]. In addition, independent component analysis for blind source separation has also been applied [13,14].

The wavelet transform (WT) is another approach that has been proposed for fetal ECGs processing. Different techniques for noise removal or/and detection of fetal waveforms have been used. More specifically, a bi-orthogonal quadratic spline wavelet was considered and the detection of the singularities were obtained using the modulus maxima [15]. Also, the Gabor-8 power wavelets combined with the application of the Lipschitz exponents were applied to extract fetal QRS complexes and P and T waves. Furthermore, wavelet-based multiresolution analysis has been proposed for noise removal [16].

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The aim of this paper is to present a method for the automated extraction of the FHR signal from the composite maternal ECG. The determination of the FHR is accomplished by finding the positions of the R-peaks. These play a major role in the analysis and diagnosis of cardiac diseases when the ECG signal is considered. Our method employs complex wavelets (CWT), complex-valued wavelet modulus maxima to detect the fetal R peaks and a heuristic set of rules based on adaptive threshold.

2. Methods

2.1. Complex CWT

CWT produces excellent results in mapping the changing properties of non-stationary signals and is also an ideal tool for determining whether or not a signal is stationary in a global sense. For a non-stationary signal, CWT can be used to identify stationary sections of the data stream and locate and characterise singularities. Given the input signal $x(t)$, CWT is defined as:

$$\mathrm{CWT}(a,b)=\frac{1}{\sqrt{|a|}}\int_{-\infty}^{+\infty} x(t)\,\psi^{*}\left(\frac{t-b}{a}\right)dt\,, \qquad (1)$$

where $*$ denotes complex conjugation, t is the time, $\psi(t)$ is the so-called mother wavelet, a (>0) is a scaling factor, and b is the translation parameter. The weighting function $1/\sqrt{|a|}$ is arbitrarily selected.

The complex CWT (CCWT) performs continuous wavelet analysis of real signals using complex wavelets. Complex-valued wavelet transform plays a special role in signal analysis. The complex nature of wavelets provides further improvement in signal detection compared to real-valued wavelet analysis. The resulted complex-valued time-frequency signal can be further analyzed by the detection of significant attributes in its modulus and phase. In this way, not only the waves can be detected but also various shapes of the waves can be identified [17].

There are several complex-valued progressive wavelets. The complex frequency B-spline wavelet (fbsp), which has been used in our method, is defined as

$$\psi(t)=\sqrt{f_b}\left(\mathrm{sinc}\left(\frac{f_b t}{m}\right)\right)^{m} e^{2i\pi f_c t}\,, \qquad (2)$$

which depends on:

i. m, the integer order parameter $(m \geq 1)$,

ii. f_b, the bandwidth parameter and

iii. f_c, the wavelet's central frequency.

Thus, the wavelet can be represented as fbsp (m, f_b, f_c).

2.2. FECG extraction method

The method includes four stages (Fig. 2). First, pre-processing is realised through signal averaging. Then, the mother heart beats are recognised in the next stage and the candidate fetal QRSs in the third stage. In the last stage a heuristic algorithm is applied to detect the overlapped fetal QRS points and discard the misdetected (false positive) QRSs.

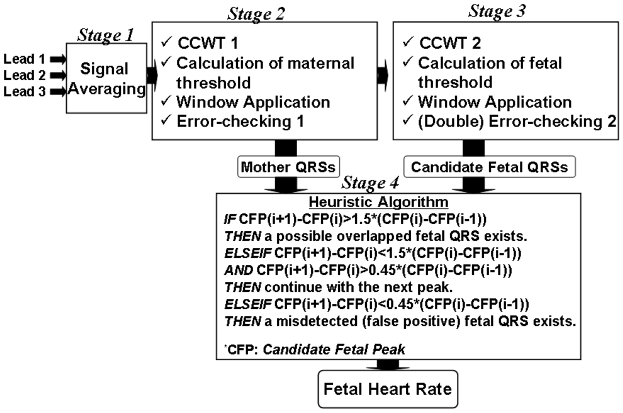

Fig. 2: The proposed 4-stage Fetal Heart Rate (FHR) extraction method.

2.2.1. Stage 1: Signal averaging

Signal averaging is performed by adding the amplitudes of the three recorded leads. In some channels, FECG is not present. Hence, averaging makes the fetal R-peaks to become distinguishable integrating the characteristics of the three recorded leads in one.

2.2.2. Stage 2: Maternal QRS detection

In this stage the mother heart beats are identified using the fbsp(3,1,0.5) wavelet. Using a scale of 1 for this wavelet, the maternal QRS complexes are enhanced more than the rest of the signal, thus, making their detection feasible. The modulus of all wavelet transform coefficients is computed. A threshold is calculated automatically equal to 60% of the mean value of the maternal highest points. The maternal QRS complexes are represented by the maximum modulus values; hence any point that exceeds this threshold belongs to a maternal QRS.

2.2.3. Stage 3: Candidate fetal QRS detection

In this stage we identify the fetal heart beats including the misdetected (false positive) QRS points but not points which overlap with the maternal waveform. The fbsp(1,1,0.5) wavelet with a scale 1 is applied. Having the MHR detected, an amplitude threshold is estimated for each interval between the two continuous maternal R-peaks. This threshold is continuously updated keeping its value equal to 60% of the highest value of the wavelet coefficients modulus. In both stages 2 and 3 an additional control mechanism is realised when a maternal or a fetal QRS complex is divided in two windows.

2.2.4. Stage 4: Fetal heart rate detection

The detection of the overlapped fetal QRS and the rejection of the misdetected QRS points is accomplished using a heuristic algorithm. Having knowledge of the Mother QRSs (MQRS) and the Candidate Fetal Peaks (CFP) we extract the Final Fetal Peaks (FFP). This is accomplished comparing CFP(i+1) - CFP(i) (difference 1) against CFP(i) - CFP(i-1) (difference 2). If difference 1 is larger than 150% of difference 2 then a possible overlapped fetal QRS exists. Its presence is verified by the existence of an intermediate maternal QRS, so the fetal and maternal QRSs are considered to coincide. In the case where difference 1 is smaller than 45% of difference 2 then a misdetected QRS point exists. So, we retain the peak with the smallest amplitude value.

2.3. Dataset

In our study abdominal signals were used, which were obtained from the FECG database of the University of Nottingham [18]. More specifically, 15 short recordings of 1 min in duration with three measurement locations for improved signal acquisition were used. The three channels of raw ECG data were recorded between the 20th and 41th weeks of gestation. The sampling frequency was 300Hz and 12-bit resolution was employed. The system uses three pairs of electrodes placed around the mother's abdomen. We don't use the thoracic signals but only the abdominal recordings.

3. Results

The proposed system is validated using the above described dataset. The obtained sensitivity and the positive predictive accuracy in fetal R-wave detection were 99.4% and 99.5%, respectively. More specifically, in a total of 1975 fetal cardiac beats the proposed system detected correctly 1954 beats (TP), missed 12 (FN) and misdetected 9 (FP). Most of the missed QRS points are located at the starting and ending segments of the recorded signals and are due to the adaptive nature of the proposed system. As for the misdetections, these are located in areas with very low SNR. Table 1 summarizes results which are obtained by other methods in the literature.

Table 1: Summary of existing methods.

Author	Method	Acc*
Mooney et al., 1995 [4]	Adaptive algorithm	100 %
Camps et al., 2001 [8]	FIR Neural Networks	91 %
Khandaker, 2001 [10]	Fuzzy Approach	89 %
Ibahimy et al., 2003 [12]	Real-time signal processing technique	88 %
Khamene & Negahdaripour, 2000 [15]	Bi-orthogonal quadratic spline wavelet	100 %
Proposed Method	***Complex CWT***	**99.5%**

**Acc:Accuracy*

4. Discussion and conclusions

A method for the automated detection of the fetal QRS complexes was developed that uses ECG recordings from the mother's abdomen. It is based on CCWT and utilizes the modulus of its coefficients. The thresholds applied to the wavelet transform (stages 2 and 3) are estimated automatically and discriminate the mother's influence from the fetus. A heuristic algorithm is applied to identify the overlapping points with the MHR and discard the misdetected QRS points.

We tested our method using real ECG recordings for the whole gestation period. The proposed method proved to be very efficient. It should be mentioned that there is a lack of a standard reference database with MECG recordings in the literature. That means that the proposed methods in the literature cannot be directly compared since they were evaluated using different datasets. The majority of the proposed detection methods were tested using either simulated signals [5,7,8,9,11,13,15] or a small number of real recordings [1,2,5,7,8,9,13,14,15,16]. The synthetic register's characteristics may be far from those of a real signal since various types of noise are embedded during an abdominal ECG recording.

We already know that wavelets have a potential advantage for signals with a characteristic morphology and especially for signals like FECG whose spectral signatures are attributed to different waveforms. Likewise, the complex nature of wavelets and usage of modulus can provide better results in detecting waveforms with a specific shape like fetal QRS complexes. CWT and DWT have already been proposed for extracting the FHR and the results are good enough [15,16]. The CCWT proposed in this work further improves the signal analysis using information from the imaginary part of the wavelets. The automated identification of the algorithm's parameters increases the system's efficacy. In addition, our approach is computationally fast and excels in performance when compared with other methods already reported in the literature. Finally, our system is able to extract the MHR signal, which can be useful for parallel monitoring of the mother's health.

The proposed FECG detection method can be further improved, in terms of noise handling. The presence of noise in long duration MECG recordings is unavoidable so proper filtering must be utilized. Moreover, a FECG database with a substantial amount of real maternal recordings should be developed to further evaluate our method. The implementation of an automated method for maternal and fetal health monitoring and diagnosis along the pregnancy period is our future objective. The already extracted maternal and fetal heart rate of the proposed method can be used in order to be analysed by a set of medical rules which can be defined in collaboration with medical experts.

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