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Foetal heart rate estimation by empirical mode decomposition and MUSIC spectrum

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ABSTRACT

It is still a challenge to estimate the foetal heart rate accurately from a strong nonstationary abdominal ECG signal. Even if signal process eliminates the predominant maternal ECG component, the foetal heartbeats are still very weak due to other existing interferences. This paper introduces empirical mode decomposition (EMD) and multiple signal classification (MUSIC) to tackle this issue. Firstly, preprocessing eliminates the interferences and noise in abdominal ECG signal and then the EMD is utilized to decompose the foetal ECG signal into a set of intrinsic mode functions, which could be used to detect the foetal QRS waves. Finally, the MUSIC is applied on the foetal QRS waves indicator sequence to estimate the foetal heart rate in the frequency domain with a high resolution. The basis functions of EMD are derived from the foetal signal under test, which makes the detection process robust and adaptive. In addition, the foetal heart rate estimation is carried out in the frequency domain regardless of the detection of R-wave peaks. In the simulated experiments with the proposed method, the mean value of the fHR estimation error is *2* BPM with a standard deviation of *1.5* at SNR = −*30* dB, and it decreases to 0 when SNR = −*16* dB. When compared to the fastICA algorithm, the proposed method shows robustness using three different real foetal ECG databases with variable degrees of nonstationarity.

1. Introduction

During gestation, monitoring of the foetal heart rate (fHR) has become a routine procedure to test the well-being of the foetus [1]. A common technique for monitoring the fHR is Doppler ultrasound [2–4], which requires intermittent transducer repositioning and, that can only be appropriately handled by for use with highly trained midwives. Moreover, the ultrasound method is not recommended for long-time recordings. As a noninvasive style, the fHR could be estimated from the abdominal ECG signals acquired by some electrodes placed on the abdomen of a pregnant woman. However, the small amplitude of the foetal QRS waves is overwhelmed by a large amount of interference and noise, such as the maternal ECG (mECG), maternal electromyogram (mEMG), powerline interference and baseline wander. Even if the mECG is removed by signal processing, the foetal QRS waves are still contaminated by other noises. Fig. 1(*a*) shows an abdominal ECG signal, and Fig. 1(*b*) shows the foetal ECG signal after the mECG component has been removed. The other interferences, such as the mEMG, make the foetal ECG signal nonstationary and it is hard to detect the foetal QRS waves accurately and effectively leading to fHR estimation error.

Various techniques have been employed to address this problem, including template subtraction [5,6], adaptive filtering [7,8], independent component analysis (ICA) [9–13], wavelet analysis [14,15], neural network [16,17], extended Kalman filtering [18,19], and Support Vector Machine [20,21]. It is more difficult to estimate the fHR from the abdominal signal, which is strongly nonlinear, nonstationary, and has a low signal-to-noise ratio (SNR). ICA is a very popular method for foetal ECG extraction, but the low dimension of the input mixture and the reduced SNR of the data undermine its performance. Wavelet analysis is a frequently used nonstationary analysis, but it needs parameter optimization before application, which is not convenient in automated application scenarios. Neural network or support vector machine methods have been employed to address nonlinear modelling, but they are often confronted with the problem of bad generalization capability, trouble of learning nonconvergence, and selecting a network structure or kernel function based on experiences. Thus, a robust nonlinear and non-stationary analysis method is required for real application.

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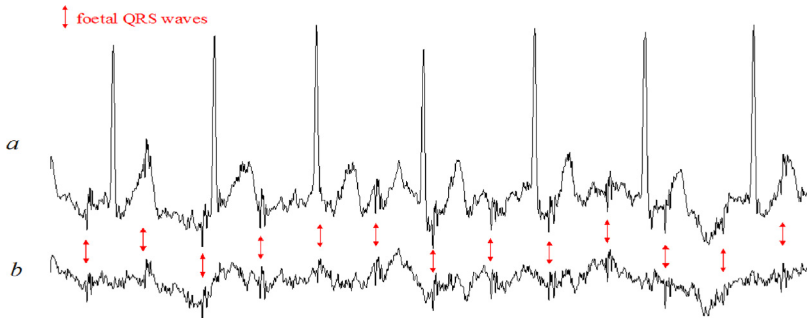

Fig 1. Foetal QRS waves in the abdominal ECG signal:(a) abdominal ECG signal, (b) foetal ECG signal after removing the mECG component.

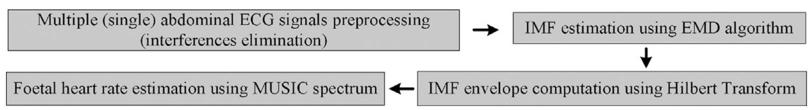

Fig. 2. A block diagram of the proposed method for fHR estimation.

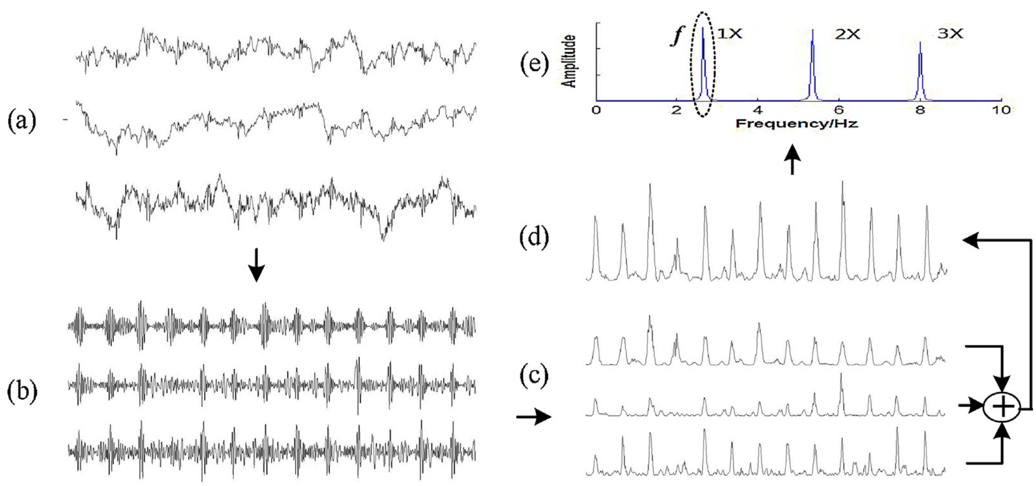

Fig. 3. A diagram of the foetal heart rate estimation process: (a) foetal ECG signals after removal of interferences, (b) imf_1 estimated from foetal ECG signals by the EMD algorithm, (c) imf_1 envelopes obtained by Hilbert transforms, (d) integrated envelope, (e) MUSIC spectrum of the integrated envelope.

On the other hand, most of the existing fHR estimation methods are based on R-waves peaks detection, and a low SNR condition may weaken their performance and so it would be useful to attempt an estimation of the fHR in the frequency domain with high resolution.

This paper introduce the empirical mode decomposition (EMD) [22] and multiple signal classification (MUSIC) [23] algorithms to address this problem for the first time. The input of the algorithm consists of multiple channels of abdominal ECG recordings from which the maternal ECG component has been removed by preprocessing. EMD has been proven to be a powerful tool for non-stationary time signal analysis and it can decompose the foetal ECG signal into a set of oscillatory functions called intrinsic mode functions (IMFs), which could be used as an indicator for the foetal QRS waves. The fHR, when estimated in the frequency domain of the foetal QRS waves indicator sequence, decreases the estimation error caused by false or missed detections in the time domain waveform. Unlike discrete Fourier transform (DFT), MUSIC is able to estimate the frequencies with a higher accuracy, because its estimation function can be evaluated for any frequency, not just those for the DFT bins, which is a form of super resolution. Thus, the fHR is obtained accurately when the fundamental frequency of the foetal QRS waves indicator sequence is estimated using the high-resolution MUSIC spectrum.

2. Method

2.1. Proposed method for fHR estimation

Firstly, the interferences and noises such as maternal ECG component, power-line interference, baseline wandering and random electronic noise in abdominal ECG signal must be eliminated in the preprocessing step. Maternal ECG component is the predominant source of interferences. To achieve this purpose, comb filtering [24], adaptive filtering [25], and support vector regression [21] methods have been previously employed by us. After that, the EMD algorithm is applied on the foetal ECG signal to estimate the corresponding IMFs, which is a collection of AM-FM components. Then, the envelopes of certain IMFs undergo by Hilbert transforms [26] to enhance the foetal QRS waves and the foetal heartbeat indicator sequence is obtained. It plays the role of demodulation to obtain the harmonic frequency component of the foetal heartbeats. Finally, the MUSIC algorithm is applied to the foetal heartbeat indicator