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Systematic Methods for Fetal Electrocardiographic Analysis: Determining the Fetal Heart Rate, RR Interval and QT Interval

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Abstract

Non-invasive fetal electrocardiographic (FECG) monitoring plays an important role for detecting and diagnosing the fetal diseases due to its negligible risk. In the present study, we aimed to propose systematic methods for accurately locating the fetal QRS complexes and estimating the QT interval in non-invasive FECG signals. The methods included 4 steps. In Step 1, we firstly used the wavelet decomposition and comb notching filter to pre-process the original maternal abdominal ECG (AECG). Then we used the entropy method to assess the signal quality. Finally principal component analysis (PCA) and signal quality flags were used to obtain an optimal AECG reference signal for maternal R-peaks detection. Step 2 determined the actual maternal R-peaks for the channels with good signal quality. In Step 3, maternal ECG (MECG) templates were constructed using the coherent averaging method and the constructed MECG signals were obtained by first compressing the MECG template according to the real length of each period and then joining period-by-period. The pure FECG signals from the channels with good signal quality were obtained by removing the corresponding MECG signals. In Step 4, after the pre-processing for the obtained FECG signals, fetal R-peaks were determined by a combination method of adaptive threshold and PCA and then fetal heart rate, fetal RR and QT intervals were determined. Our best entry results on set B were: average score for event 4 is 264.87 and average score for event 5 is 9.04, which is a significant improvement compared with the sample submission (event 1/4 is 3258.56 and event 2/5 is 102.75).

1. Introduction

Fetal electrocardiography (FECG) monitoring in labour is of very important for detecting fetal well-being and diagnosing the possible diseases of fetal heart since the mid-1970s [1, 2]. FECG can be obtained by applying an intra-uterine electrode on the fetal scalp or be carried out through skin electrodes attached to the mother's abdomen [3]. The use of an intra-uterine scalp electrode could obtain better quality as compared with non-invasive skin electrode; but it is highly invasive and is limited to recordings during labour, after the breaking of the amniotic fluid [2, 4]. In contrast, abdominal FECG provides a non-invasive method to detect fetal well-being during both pregnancy and delivery. Moreover, it could offer the possibility for long-term monitoring the basal heart rate, its variability and the development of a process of hypoxia [5] and provide valuable parameters such as fetal heart rate (FHR), fetal RR and QT interval [6].

However, FECG recorded from the mother's abdomen is inevitably contaminated by a variety of interference signals and noises. Among them, mother ECG (MECG) is usually the dominant interference source and has much larger amplitude than FECG. Other noises include baseline drift, respiration interference, power-line interference, electromyogram (EMG) and motion artefacts [2, 4, 7]. Numerous attempts have been made to retrieve the real FECG from the abdominal recordings but the difficulties of signal processing techniques still lurk. To better understand the state-of-the-art research, reference [2] is recommended.

The aim of this study was to develop a new and robust algorithm for the analysis of 4-channel abdominal FECG recordings and test its performance in the Computing in Cardiology Physionet Challenge 2013 [6].

2. Methods

2.1. Database

Data for the Challenge consist of a collection of one-minute FECG recordings. Each recording includes four non-invasive maternal abdominal ECG (AECG) and they are presented as 1000 samples per signal per second. The reference annotations for each recording for each fetal QRS complex were produced by experts with reference to a direct FECG signal, acquired from a fetal scalp electrode. Three data sets were provided for the algorithm analysis and test [6]:

♦ Training Set-A: with 75 AECG recordings and their reference annotations.

* These authors contributed equally to this work.

♦ Open test Set-B: with 100 AECG recordings but no reference annotations for evaluation of challenge events 4 and 5.

♦ Hidden test Set-C: unpublished records for evaluation of open-source challenge events 1, 2, and 3.

2.2. Algorithm description

Figure 1 showed the algorithm flow chart. The proposed algorithm for the detection of fetal heart rate (FHR), fetal RR and QT intervals consisted of four steps. Step 1: AECG pre-processing; Step 2: Maternal R-peaks detection; Step 3: MECG cancellation and Step 4: Fetal R-peaks location. Each step consisted of several sub-steps.

In Step 1, the wavelet decomposition method was used firstly to remove the trend of 0~8 Hz from the original AECG signals. Then a comb notching filter was employed to remove the power line interference. Afterward, two steps are executed in parallel: quality assessment and principal component analysis (PCA).

1) Quality assessment: the sample entropy (SampEn) of each AECG channel was calculated. Signal in each channel was divided into 6 non-overlapping episodes (10 s each) and the mean of their corresponding SampEn values was returned as the SampEn result of the present channel. Signal quality was assessed by comparing SampEn values in each channel with a constant threshold value, which was empirically set at 1.5. More proportion

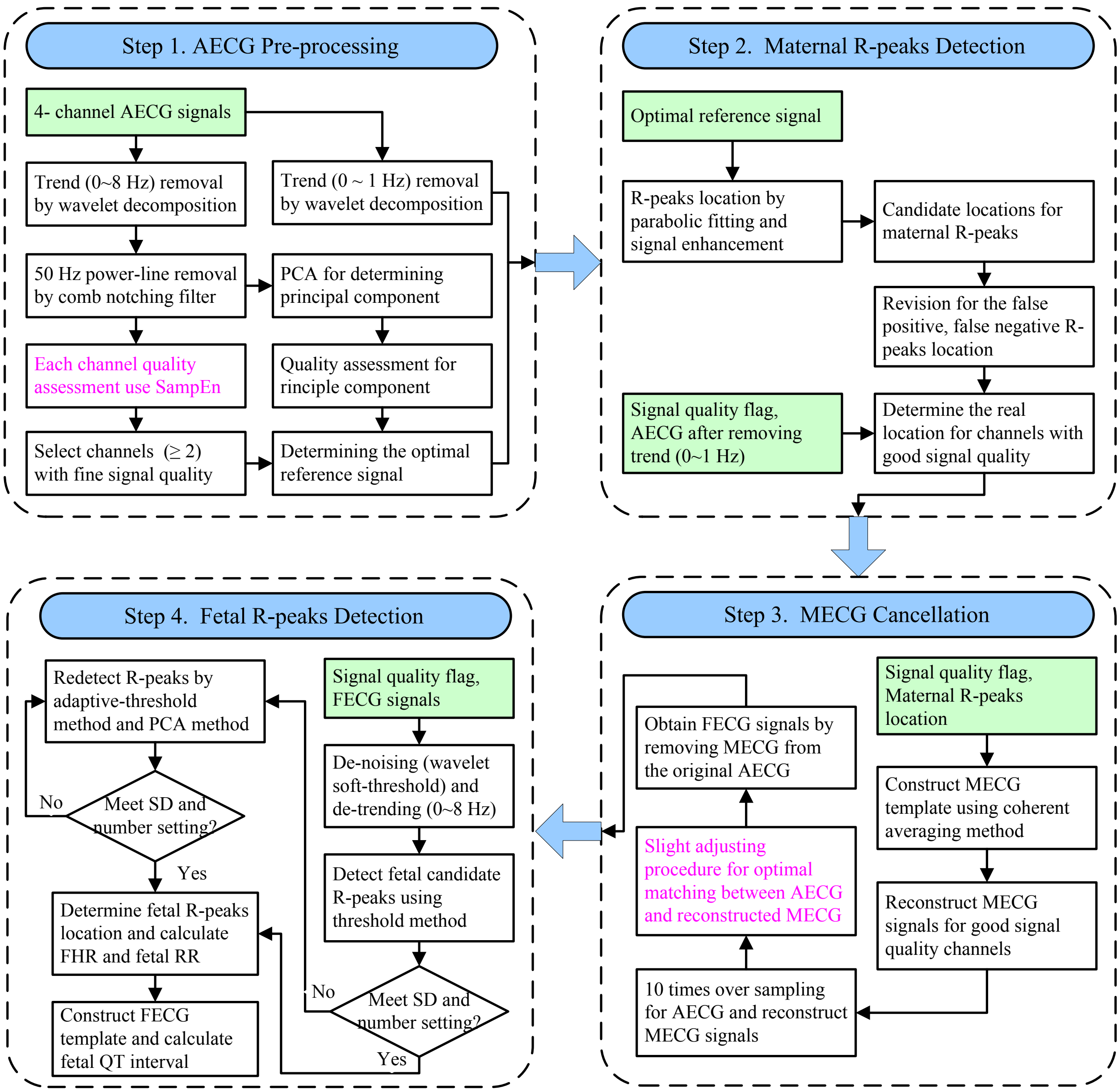

Figure 1. Algorithm flow chart

of Gaussian noise has, larger SampEn is. So channels with SampEn value higher than 1.5 were regarded as poor quality and excluded for the following analysis in Step 2, 3 and 4. However, if less than 2 channels of good quality returned accordingly, the 2 channels with the smallest and penultimate SampEn values were remained.

2) PCA: the AECG signals after the comb notching filter were analyzed using PCA method to detect the principal component. Then the signal quality of principal component was also assessed by the entropy method.

Based on the quality assessment results of the filtered AECG signals and its principal component, an optimal reference signal was determined. It could be the first principal component according to it is with good quality, or be the channel with the smallest SampEn if the SampEn of the principal component was higher than 1.5 times of this smallest SampEn. The optimal reference signal, as well as another pre-processed AECG signals, which have been removed the trend of 0~1 Hz using wavelet decomposition and been removed the high frequency noise by wavelet soft-threshold de-noising, were inputted into Step 2.

In Step 2, the candidate locations of maternal R-peaks were determined by a threshold method, which employed the parabolic fitting and logarithmical enhancement. The false positive, false negative of R-peaks location were detected and revised [8]. Then the actual maternal R-peaks from the channels with good signal quality could be detected according to those candidate locations.

In Step 3, MECG templates for each channel with good quality were constructed using the coherent averaging method. MECG template was the average of ECG episodes from one R-peak to the subsequent one. All episodes were first stretched to 2000 points length to facilitate the average processing. Besides, two adjacent R-peaks with abnormal amplitudes and intervals were excluded. Afterward, the constructed MECG signals were obtained by first compressing the MECG template according to the real length of each period and then joining period-by-period. After that, a slight adjusting procedure was used to achieve the optimal matching between the filtered AECG and reconstructed MECG signals, by 10 times over sampling for both filtered AECG and reconstructed MECG beat-by-beat and then shuffling the reconstructed MECG to achieve the optimal matching. Finally, the pure FECG signals from the channels with good signal quality were obtained by removing the corresponding MECG signals.

In Step 4, FECG signals were firstly de-noised by also the wavelet soft-threshold approach, and then de-trended (0~1 Hz) by wavelet decomposition. After that, we used threshold method to detect fetal candidate R-peaks for each channel with good signal quality. Standard deviations (SDs) from each fetal RR interval sequence were compared and the fetal RR interval sequence with the smallest SD was selected as the candidate fetal RR interval sequence. If two conditions are met: SD<90 and the fetal beat number is more than maternal beat number, then this candidate fetal RR interval sequence was accepted as the final sequence. If not, we reemployed two methods to determine the fetal RR interval sequence independently: adaptive-threshold method and PCA method.

1) Adaptive-threshold method: this method could adaptively adjust the threshold for peaks detection for each good signal quality channel.

2) PCA: the FECG channels with good signal quality were analyzed by PCA method to acquire the principal component of FECG and then the peak detection was implemented to detect the candidate locations of fetal R-peaks.

The results from above two methods were also compared and the optimal sequence with the smallest SD was selected as the final fetal RR interval sequence, from which the FHR and fetal RR were determined. After that, the FECG template was also constructed using the similar method of the MECG template, and the fetal QT intervals was determined by this template.

3. Results

Figure 2 gives a good demonstration for fetal R-peaks detection results. Although the original AECG has obvious baseline shift, the signal quality of this AECG is fine. The obtained FECG signals are easy to detect the R-peak. So the estimated FQRS is almost same as the answer FQRS.

Figure 3 shows an effective example when using the signal quality assessment technique based on the entropy. Channel 1 is mainly the system noise and channel 3 has much noise of high frequency, so their SampEn are higher than 1.5, indicating the poor signal quality of them. These two channels were excluded for the fetal R-peaks detection and the final result showed it could obtain accurate detection even if using the remained 2 channel signals.

Figure 4 shows an effective example when using slight adjusting procedure for reconstructed MECG. At the bottom panel of Figure 4, black line shows the raw AECG and green line shows the reconstructed MECG. Sometimes there are some shifts between two signals. Although the shifts are small, they will cause fatal interference for the fetal R-peaks location. So the adjusting procedure for reconstructed MECG is need. The red line shows the MECG after adjusting procedure and it could match the raw AECG better. The fact that the FECG signal at the maternal R-peaks locations is not very noisy shows the effect of this adjusting procedure.

Table 1 shows the performance of our proposed method in comparison with the sample one. On testing Set-B, our method scored 264.87 for event 4 and 9.04 for event 5, performing respectively 12 and 11 times better than the sample one.

Table 1. Performance of our proposed method in comparison with the sample one.

Set-B	Sample algorithm	Our method
Event 4	3258.56	264.87
Event 5	102.75	9.04

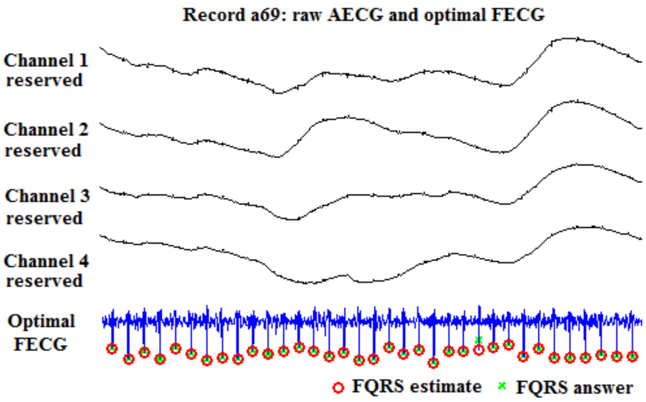

Figure 2. A demonstration for fetal R-peaks detection results when signal quality of the original AECG is fine.

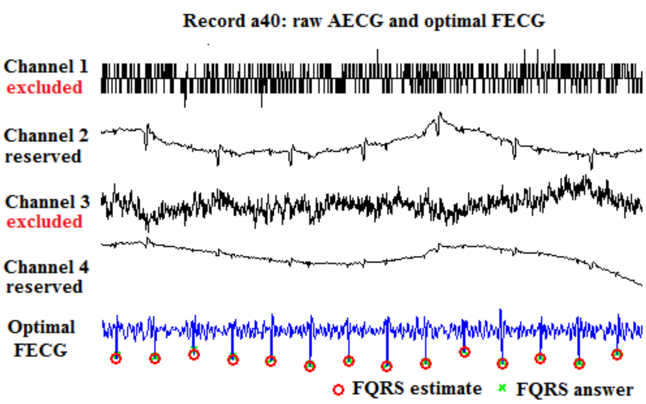

Figure 3. An effective example when using signal quality assessment technique.

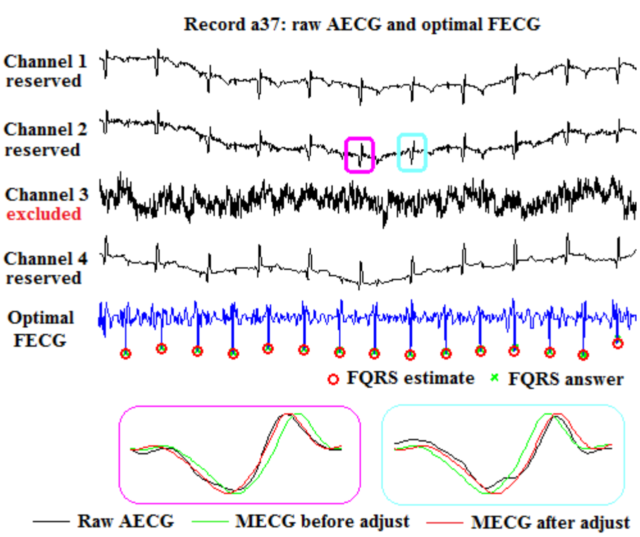

Figure 4. An effective example when using slight adjusting procedure for reconstructed MECG.

4. Conclusions

We have proposed a systematic method for determining the FHR, fetal RR and QT intervals from maternal abdominal ECG. This method performs well even in situation that 1 or 2 channels of original AECG signals were seriously polluted by noises. However, in situation that FECG signal are really weak, even could not be visually identified, the detection results of the proposed method seem not good. Further development by incorporating the artificial intelligence methods will facilitate to improve the performance of the present method.

Acknowledgements

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