Fetal Heart Rate Discovery: Algorithm for Detection of Fetal Heart Rate from Noisy, Noninvasive Fetal ECG Recordings

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Abstract

Fetal heart rate variability is known to be of a great meaning in assessing fetal health status. The simplest way of measuring fetal heart rate is to the non-invasive fetal ECG (fECG). A novel and efficient algorithm for detection of fetal ECG is needed.

We analyzed 75 FECG recordings from the PhysioNet Challenge 2013 database. The detected RR interval peaks were compared with fetal scalp electrode measurements.

Our algorithm focuses on detecting the most prominent part of the fetal QRS complex i.e. the RS slope. First, we remove long-range trends and find the two channels with the best quality fetal ECG. Then, we localize the repolarisations having the required characteristics (adequate amplitude and slope). Note, that the algorithm is adaptive and finds by itself the optimal RS slope characteristics for every recording.

These steps allowed us to obtain accurate and reliable results of fetal R peak detection, even in the case of very noisy data. The preliminary test score of the PhysioNet Challenge were 132.664 (event 4) and 11.961 (event 5). The phase 3 score of the PhysioNet Challenge were 118.221 (event 4) and 10.663 (event 5). This is an open-source algorithm available at the PhysioNet library.

1. Introduction

Heart rate analysis provides a unique insight into the activity of the fetal autonomic nervous system, enabling prenatal diagnosis of the fetal development [1-3,7]. Moreover, analysis of the fetal ECG (fECG) waveform would give an insight into congenital heart defects of the fetal heart [4]. To perform such analysis, an accurate method of recording fetal heart rate and RR intervals is necessary. One way is to use fetal magnetocardiography - a noninvasive technique to detect magnetic field generated by the activity of the fetal heart [5,7]. However, being a costly method, it is impossible to be implemented in hospitals world-wide. Another way is to use non-invasive fetal electrocardiography (fECG) [6]. Unfortunately, in fECG, the amplitude of the fetal QRS complex is often small in comparison to the maternal QRS complex and usually we need to remove the mother's ECG. Moreover, the electrode placement on the mother's abdomen is known but the position of the child with respect to the placement of electrodes is not clear. Last but not least, the signal is almost always very noisy (e.g. because of the mother's muscles contractions), and the signal-to-noise ratio of the fetal ECG is low.

Therefore, although the technique to acquire fECG was introduced into clinical practice in the 1970s [6], up to now signal processing techniques have been struggling to deliver a reliable estimation of QRS complexes and fetal fECG waveform estimates, such as the fetal QT interval. As a consequence, there are no standards and guidelines to assess these features.

This article addresses the specific problem of locating the fetal QRS complex in the fECG recording. The approach described here is specifically designed to provide a method to obtain accurate and reliable results of the fetal R peak detection in the case of a very low amplitude of the fetal QRS complex for fetal heart rate variability analysis. A secondary aim was to estimate the fetal QT interval - the problem addressed by PhysioNet/ Computing in Cardiology Challenge of 2013.

Since we set out to detect the fetal QRS complex location from signals with low fetal QRS amplitude, we look for a method that will induce as low distortion to the original waveform as possible.

2. Data

Data were provided by the PhysioNet/Computing in Cardiology Challenge 2013. The data consisted of a collection of four channel noninvasive ECG recordings from the mothers' abdomen (aECG). The data were obtained from multiple sources using a variety of instrumentation. Each recording has 4 channels, a sampling rate of 1 kHz and a duration of 60 s. The data was divided into three sets: (A) learning set of 75 fECG signals with reference annotations from a direct fECG signal, acquired from a fetal scalp electrode. (B) an open test set of 100 fECG signals and (C) an unpublished set of records.

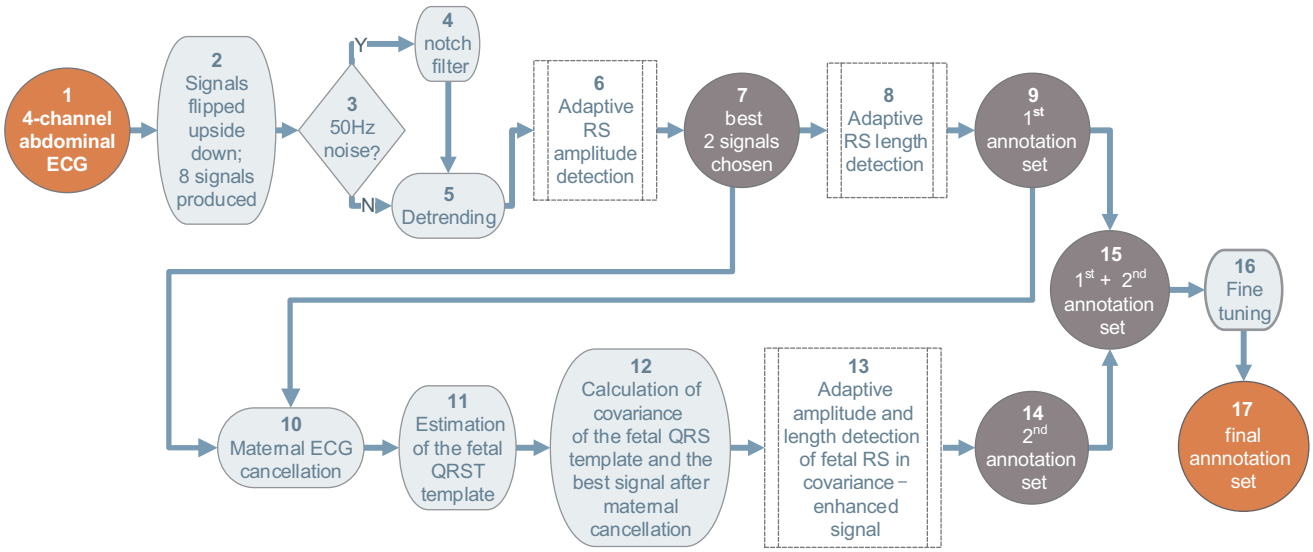

Figure 1. Flow chart of the fetal heart rate discovery algorithm. Four channels of each recording are processed in 17 steps, briefly described in section 3.

3 Methods and results

Our algorithm focuses on detecting the most prominent part of a fetal QRS complex i.e. the RS slope (see Figure. 1). It can be divided into four main parts: pre-processing of the signal (steps 1-5), RS slope detection (6-9), covariance signal enhancement (10-14), fine-tuning (15-17). Since the algorithm consists of many steps we describe briefly the prominent parts of the algorithm.

3.1. Preparation of the signal

Steps 1-2: Since the deflection of the fetal QRS (fQRS) complexes may be downward or upward in compared to the maternal ECG (mECG, see Fig.2), all 4 signals are flipped upside down, and the total of 8 signals are processed in the further part of the algorithm.

Steps 3-4: In some signals 50 Hz (and 60 Hz) noise is present in some channels . We detect if noise filtering is necessary based on the power spectrum for each channel. We check if the maximum power in the range between 49 and 51 Hz (and 59 to 61 Hz) is more than 30 times greater than maximum power between 47 and 49 Hz. If yes, we perform notch filtering of the signal. The criterion parameters are based on the analysis of set A.

Step 5:As a next step, we perform detrending on all 8 signals using a moving median with a window of 100 samples (100 ms). The width of the window was chosen so as not to alter the fQRS complex.

3.2. RS slope detection

Step 6: Next, we perform fetal RS slope detection by a dedicated adaptive procedure. The algorithm looks for such a fetal ECG RS slope that begins from a certain range of potentials in signal, i.e. we assess the amplitude of the fetal QRS complex. Based on the test set A, we experimentally found that the upper boundary does not exceed 99% of the signal distribution (the last 1% will be from the maternal ECG), and the lower boundary is always larger than 79%. (see fig. 3). We found that the length of the RS slope may be from 5 to 30 samples, depending on the signal, and the S deflection is often less than 0 in the detrended signal.

These values (i.e. the amplitude boundaries and slope lengths) have to be adaptively chosen for each signal. To do that, we take all pairs from 8 signals. In each pair of signals, we find the locations that match the criteria for the amplitude between 79% and 99% of the signal distribution width and length between 7 and 25 ms. We change amplitude ranges in steps of 2% and perform the same search for all possible choices of boundaries.

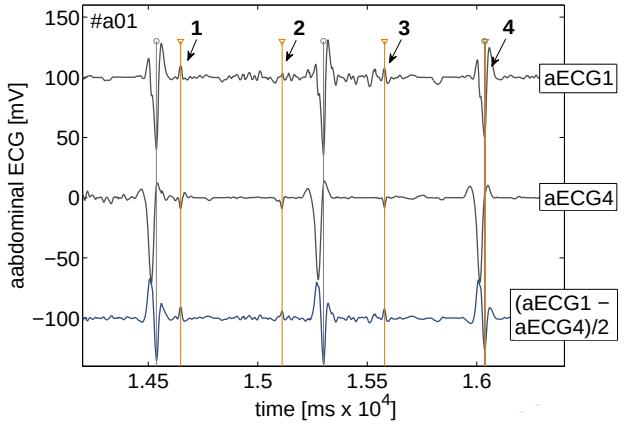

Figure 2. Example of two channels (1 and 4) from an abdominal ECG recording from set A. Note, that in channel 4 (middle signal), the fetal QRS complexes are reversed. There are four fetal QRS complexes in the figure. The 1st complex is visible in both channels. The 2nd complex in channel 1 is in the noisy area. The 4th complex is merged with the maternal QRS.

between 79% and 99%. For each combination we assess the quality of the locations we had found. We calculate the mean fetal RR interval from the annotations: their distance from each other was 300 ms to 525 ms. We leave only those RS locations, for which the RR intervals are within 75ms from the estimated mean interval

In the next step, we check the number of locations matching in both signals from the pair for all tested combinations of amplitude ranges. Based on the largest number of matching locations, we estimate the best values for the range of amplitudes of the fetal QRS complex. We also choose the best pair of signals and calculate the mean the signal from that pair. In the following part of the article, we refer to that mean signal as the 'base signal'.

Similarly, we find the best range of RS slope length, but only for the base signal. As a result, we obtain the first set of annotations for the signal. This set consists of around 20-80% of all annotations of the fQRS positions.

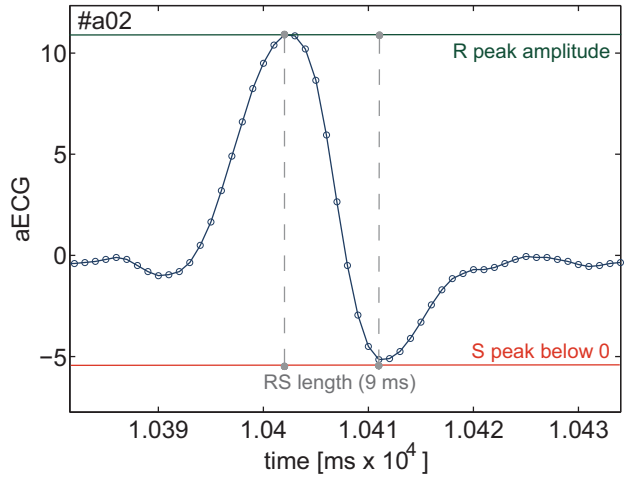

Figure 3. We detect the best recognisable part of the fetal QRS complex i.e. the RS slope. In the detrended signal, we search for the repolarisations of a certain length and R peak amplitude.

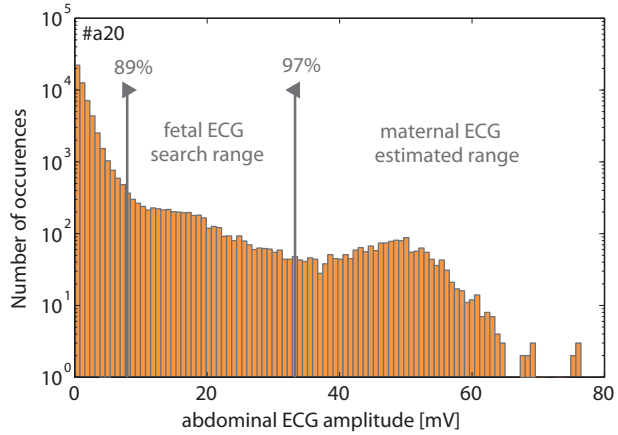

Figure 4. Histogram of the detrended signal (note the logarithmic scale). For the a20 record, the optimal boundaries for R amplitude detection were found to be 89% and 97%.

3.3. Covariance of the fetal QRS template with the signal

At the beginning of this part, we perform a search for the maternal QRS in the base signal in a way similar as we do for the fQRS in the whole algorithm. We calculate the mean, normalized template mQRS. For each mQRS complex, we multiply the template to match the mean value of the absolute of the QRS potential in the template and the detected mQRS complex, and subtract the template from the signal to remove maternal ECG.

We estimate the mean child QRS complex, based on the previous steps of the algorithm. Then, the covariance of the mean child QRS complex with the detrended, mother-signal-cancelled base signal is calculated in a moving window of 60 ms width, producing a 'covariance' signal of 60 s length. As the next step, the detrended, mother-signal-cancelled base signal is multiplied by the 'covariance' signal. We perform an adaptive RS slope detection on the covariance enhanced signal This allows to detect the fQRS in noisy areas and inside the mQRS (fig.5).

After that step, most of the missing annotations should be found. Still, a fine–tuning of the annotations are necessary.

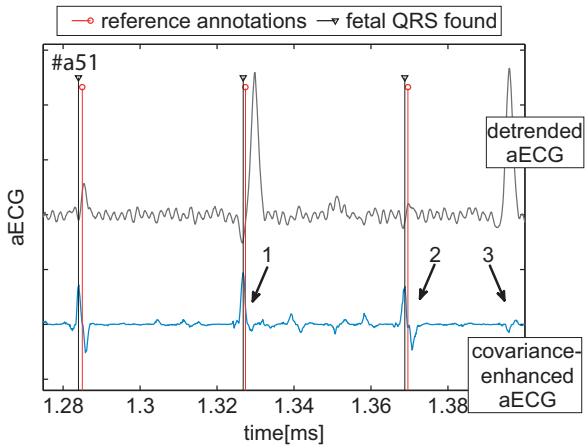

Figure 5. Example of the a51 record. Detrended aECG signal (upper) compared to covariance–enhanced signal (below). In case of a low signal-to-noise ratio of the fetal ECG, the covariance-enhanced signal helps to find fetal QRS complexes. (1) fQRS from fused complexes are still clearly visible in covariance-enhanced signal even in the case of a noisy signal. (2) fQRS, which have been covered by noise is found in the covariance–enhanced signal. (3) The maternal ECG is not present in the covariance-enhanced signal. Note the difference between the location of the fQRS found in the covariance-enhanced signal and the reference annotations – the difference is cancelled in the fine-tuning stage of algorithm.

3.4. Fine-tuning

Next, the final steps of "fine-tuning" are done. We remove the incorrect detections (ones that are

physiologically to short). In the case of possible missing annotation, we re-check the area and perform RS detections with a larger amplitude and length range.

3.5. QT interval estimation

Since our aim was to obtain the best RR interval annotations, the QT interval estimation is straightforward. We calculate the mean fQRST complex in the (not detrended) base signal. Then, we locate the Q position as the first maximum before the R wave and the T position as located at a minimal value between 100ms and 400ms from the position of the Q wave. (fig. 6).

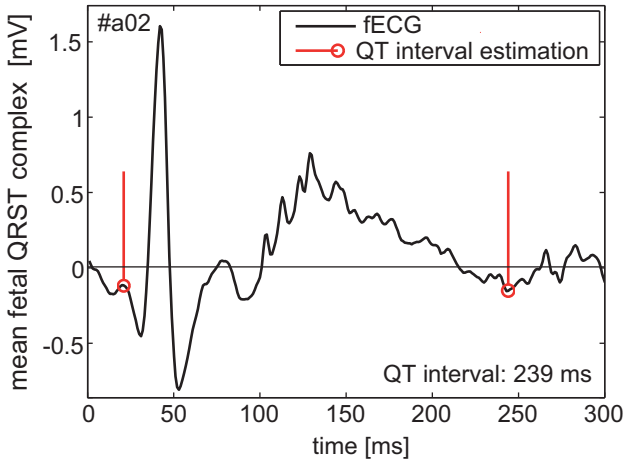

Figure 6. Fetal QT estimation

4. Results

With all features combined, the phase 3 score of the PhysioNet Challenge were 118.221 (event 4) and 10.663 (event 5).

5. Discussion and conclusions

A method for the detection of fetal QRS presented in this paper is a novel and completely universal approach. It takes full advantage of the fact that the RS slope is the best recognisable part of the fetal QRS complex. The algorithm is suited for signals with both downward or upward deflection of the fetal QRS in regard to maternal ECG.

The presented approach works especially well for partly–noisy signals, since the covariance enhanced signal in this case can be based on a well-defined fQRS template from the non-noisy part of the signal and, after calculating covariance, the template can be found in the noisy area.

It is also important to note that the results of our approach are not degraded by rapid changes of the fetal HR or an extremely high ratio between the amplitude of the maternal ECG and of the fetal ECG.

Note, that in some cases an extensive noise filtering is necessary and a simple notch filter for 50/60 Hz seems to be not sufficient for very noisy data.

Apart from the need of better noise–filtering approach, further improving the accuracy, turned out to be hardly feasible in the chosen feature space. Because of that further work on the algorithm should focus on incorporating the information from all of the channels every record, not only from two best ones.

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