Non-invasive Fetal Multilead RR Interval Determination from Maternal Abdominal Recordings: the Physionet/CinC Challenge 2013

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Abstract

The PhysioNet Challenge 2013 focused to develop accurate algorithms for locating QRS complexes and estimating the QT interval in noninvasive fetal ECG (FECG) signals obtained from noninvasive abdominal recordings in pregnant women.

We upgraded our custom automated software used previously. To cope with signal having different frequency contents we derived and analyzed two sets of signals using two different bandpass filters. The mother ECG (MECG) cancellation was performed using P, QRS and T wave templates and with appropriate scaling and shifting of P and T waves due to QT and PQ variability. From the cancelled signal, true fetal beats were extracted with a FQRS filter assuming that the error variability due to deviations of detected beat intervals from the median RR interval should be minimal. By selecting the lead with the smallest error and interpolating missing beats we obtained the final fetal QRS positions.

The accuracy of determination of FQRS positions of our algorithm was tested by comparing our derived FQRS sequences with the reference annotations for the learning test set of 75 recordings. For the PhysioNet 2013 Challenge on set B from we obtained an average score 181,2 for fetal HR estimation accuracy, score 10.92 for fetal inter-beat accuracy.

1. Introduction

The aim of the PhysioNet/CinC 2013 Challenge was to develop accurate algorithms for locating QRS complexes and estimating the QT interval in noninvasive fetal ECG (FECG) signals [1,2]. Multiple challenge events in which we participated included fetal hear rate (FHR) estimation accuracy and fetal inter-beat (RR) accuracy.

Data for the challenge consisted of a collection of one-minute fetal ECG recordings, with each recording includes four noninvasive maternal abdominal signals with the sampling rate 1 kHz, obtained from multiple sources using a variety of instrumentation with differing frequency response, resolution, and configuration. In each case, reference annotations marking the locations of each fetal QRS complex were produced, usually with reference to a direct FECG signal that was not included in the challenge data sets, however.

The learning set A included noninvasive fetal ECG signals and the reference annotations for them, whereas the Open test B included noninvasive signals only, and was used for evaluation of challenge entries.

In the challenge we participated in the events for the FHR and fetal inter-beat accuracy.

2. Methods

We upgraded our custom automated software from the previous Challenges [3,4] using the sequential algorithm similar to Suzanna Martens et al [5] and applying the following ideas. First, to cope with signal having different frequency contents, particularly due to excessive noise, we derived two sets of signals from each measured signal using two different band pass filters, one with lower pass than another. Second, we performed MECG cancellation using P, QRS and T wave templates and with appropriate scaling and shifting of P and T waves due to QT and PQ variability. Third, to find true fetal beats and lead specific signals containing best information for FQRS, we created a FQRS filter that provided FQRS series and FQRS error, based on minimization the local RR variability, excluding beats with deviations less than 1/8 of the median RR interval. Finally, FQRS series from 8 lead specific and two combined signals were used to get the representative FQRS series based on the smallest FQRS error.

Automated analysis (Pascal, Delphi 5.0, Borland) was performed without intervention of an external operator.

2.1. Signal preprocessing

Signals were preprocessed using median filtering to remove spikes. Then each of four measured maternal abdominal signals was filtered with two sets of slightly different bandpass filters, a high-pass to remove baseline wandering and a lowpass to remove high frequency noise. We used a two pole high-pass and a four pole low pass Chebyshev filters to get two bandpass windows, 5 - 40 Hz

and 1 - 80 Hz, respectively. By applying each of these two band-pass filters on each ECG signal we obtained 8 signals that appropriately amplified to have peak to peak amplitude at least 1000 units.

2.2. MQRS detector

R wave peaks of maternal QRS complexes (MQRS) were identified with an automated peak detection algorithm proposed by Pan and Tompkins [6]. For this purpose we constructed a global signal, represented by a squared sum of the time derivative, $\sum(dU/dt_i)^2$, of each of 8 signals that was integrated in the moving -window of 80 ms. The resulted trigger signal was then time differentiated and normalized to the highest amplitude and its rising edge above the threshold represented the fiducial mark.

2.3. MECG cancellation

The derivative signals dU/dt_i were used again to construct a global RMS signal and by mutual comparison of beats using the cross-correlation, a correlation matrix was obtained that enabled separation of beats into clusters. This was used as the criterion for selection of maternal beats in the construction of the templates.

Templates of the P, QRS and T wave of the maternal ECG were obtained by averaging beats belonging to the same cluster. For the construction of templates we used our time shifting method considering an appropriate delay of the waves due to the QT and PQ variability [3]. The mother ECG (MECG) was removed by subtracting the appropriate templates for the P, QRS, and T waves separately. For this purpose we determined scaling factors for each beat and for each ECG wave. This was based on finding a factor that minimizes the integrated squared difference between each particular beat and the template in the appropriate interval of a given ECG wave (least-mean square method). The derived 8 fetal signals were then used for detection of fetal beats.

2.4. FQRS detector and fetal trigger signal

We used a similar QRS detector as used for the maternal ECG, but separately for each fetal lead signal, integrating thus $(dU/dt_i)^2$ and in time window of 60 ms. Such window-integrated signal was then differentiated with respect to time and positive values above certain threshold provided the fetal trigger signal. Fiducial points of the resulting signal provided 8 series of provisional fetal QRS positions (FQRS series) and 8 series of provisional fetal RR signals (fetal RR series). As the derived FQRS are in generally much lower in amplitude than the maternal ones, they are expected to be noisier with many false positive peaks that might have arisen. On other hand, some fetal QRS peaks might have been removed due to MECG cancelation if they coincided with maternal beats or with heavy noise. Indeed, FQRS detector provided many false positive QRS peaks with many missing peaks, therefore a filter for detection of true FQRS to provide FQRS signal was necessary.

2.5. FQRS filter and FQRS error

FQRS filter was based on comparison of locally limited group of detected peaks with a reference group of 11 beats, separated by the local mean RR interval. We assumed that for a true beat the deviation from the corresponding reference beat should be limited.

First, for a given fetal signal we performed the frequency analysis of the FQRS series to determine median fetal RR interval, RR_{med}, accepting only RR intervals in the region between 300 and 650 ms. Then, we constructed a reference grid with 11 time markers, G_k, ($1 \leq k \leq 11$) that were separated by 10 intervals with a fixed width, equal to the local mean RR interval, $RR_{m,local}$. The grid was moved along each of the FQRS series, and by adjusting $RR_{m,local}$ we were searching for best local matching of the grid with FQRS positions.

For this purpose, deviations of j-th QRS position, P_j, from the nearest grid peak position, G_k, $\Delta P_j = P_j - G_k$, were determined for each P_j within the range of the grid. Only beats with deviations smaller than $RR_{med}/4$ were considered as true fetal beats for a given signal. In addition, we calculated local error ψ, defined as the sum of squared deviations in the range of the grid.

We considered only deviations bigger than $RR_{med}/8$, and those bigger than $RR_{med}/4$ were taken to be equal to $RR_{med}/4$. By neglecting deviations smaller than $RR_{med}/8$, we took into consideration that physiological RR variability should not contribute to the error. For the m-th movement of the grid with respect to the beat position signal, we obtained:

$\psi_m = \sum(\Delta P_j)^2$, for $1 \leq j \leq N_m$,
N_m = number of FQRS within the grid range.
$\Delta P_j = 0$ if $\Delta P_j \leq RR_{med}/8$ and
$\Delta P_j = RR_{med}/4$ if $\Delta P_j \geq RR_{med}/4$

The lead specific FQRS error for the i-th lead signal, Err_i, was obtained by summing all local errors ψ_m while moving the grid from the beginning to the end of the signal, where m runs from 1 to the number of FQRS. In addition, this sum was divided with the square of the number of accepted fetal beats to get

$$Err_i = \sum \psi_m / n^2,$$

with n as the number of the accepted fetal beats in the lead i. Thus, Err_i increased by both, the increased number of missing beats and increased number of false fetal

peaks, which enabled further selection of leads acceptable for the fetal RR series.

Missed fetal beats were determined by interpolating the appropriate number of missing beats between two successive provisional fetal beats when their separation was greater than $1.75*RR_{m,local}$.

2.6. Optimization of the trigger threshold

FQRS trigger signals exhibited peaks with different amplitudes, and not all peaks represented the fetal beats. We speculated that the criterion for the inclusion of a certain peak among the true fetal beats could depend on the threshold, required for a particular peak to overcome. We expected that by increasing the threshold, less beats would be included in the beat position signal, reducing thus the number of false peaks. For this purpose we were increasing the trigger threshold trigger until finding the smallest FQRS error, separately for each of 8 lead specific FQRS signals (Fig. 1).

By obtaining FQRS error it was possible not only to select the best lead for determination of individual fetal beat position series, but also to combine the most acceptable lead specific fetal signals for construction of a global signal, from which an additional trigger signal would be obtained using the moving window-integration procedure. The criterion for the selection of the acceptable leads was the lead specific FQRS error, Err_i. The lead with the smallest error was selected first, and all leads with Err_i less than twice the smallest one were also accepted.

2.7. Combined FQRS signals

Two different procedures were applied. First, the accepted signals were decomposed using PCA, and the first principal signal was used to derive the trigger signal. In the second one, we used the squared derivative signal, $\sum(dU/dt_i)^2$, and derived the trigger signal, similarly as used for the construction of the trigger signal of MECG, with the exception of using the accepted fetal signals only. From thus obtained two trigger signals, two appropriate FQRS series and FQRS errors was calculated.

2.8. Global FQRS series

All FQRS series so far obtained were used to get the global FQRS series that incorporated properties of all particular RR series. For this purpose we superimposed all acceptable FQRS series, i.e. those with error Err_i smaller than twice the smallest one. Then, we treated it as a trigger signal with many false positive peaks and performed the procedure described in the section 2.5. In case of finding many QRS peaks for a particular beat, when beats from signal specific or global FQRS series had slightly different position, but were identified as true, we used a median value for that beat. Again we determined the appropriate FQRS error.

Finally, the representative FQRS signal of each recording that entered the Challenge was that one with the smallest FQRS error.

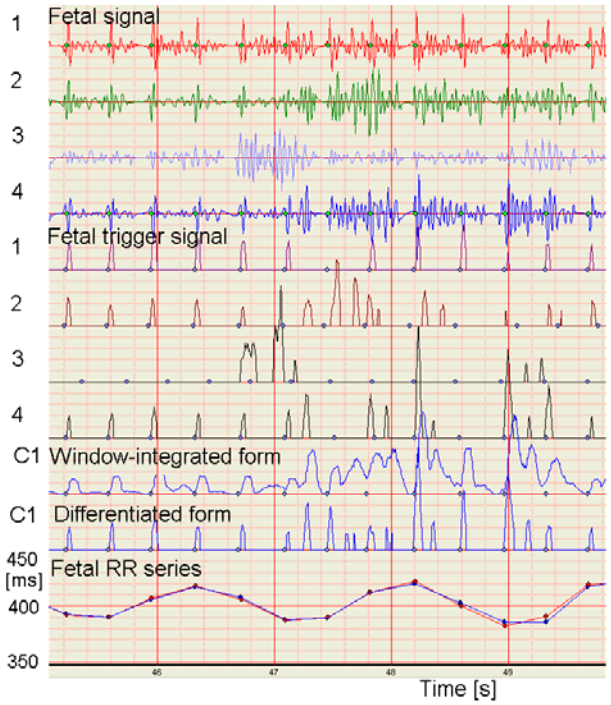

Figure 1. Fetal signals, trigger signals and RR interval series. Fetal ECG signals (1-4) with removed MECG were used to obtain the corresponding trigger signals in the time differentiated form above the optimal threshold (1-4), shown for the recording #1 of the test set A. The combined trigger signal C1 in the window-integrated and differentiated form with the optimized threshold (light blue) was obtained using fetal signals 1, 4, 5 and 8 (the last two not shown). Reference annotations are shown in fetal signal 1 and 4 (light green), and detected FQRS positions are shown in the time differentiated trigger signals 1-4 (blue). The derived (blue) and the reference fetal RR series (red) are presented at the bottom.

2.9. The performance test

The accuracy of determination of FQRS positions of our algorithm was tested by comparing our derived FQRS sequences with the reference annotations for the learning test set of 75 recordings.

For this purpose, for each reference beat of the test recording, we were looking for the closest derived FQRS position, and compared the corresponding RR intervals to get the RMS error. If the mutual distance was less than

100 ms, then the local error was taken as the squared difference between the reference and derived RR intervals, else the error was equal to the squared reference FQRS interval. The final score was obtained by summing local errors over all reference beats, divided the number of beats and square-rooted. The smaller the score, the better was result for a given recording.

3. Results

For the PhysioNet 2013 Challenge on set B we finally obtained an average score 181.22 for fetal HR estimation accuracy, score 10.92 for fetal inter-beat accuracy.

The score of the earliest entry was the highest (the scores 963.8 and 15.45) and was considerably improved later due to evolution of the analytical tools. Thus in our first entry we used smaller number of analytical steps, using unique amplification and single bandpass filtration of the signal, and finally using PCA to get one FQRS series with a FQRS filter that was later improved.

In the next, more successful entry (the scores 195.8 and 15.45, respectively) a recording specific amplification and two different bandpass filters were used but without FQRS filter.

4. Discussion and conclusions

When studying the influence of different steps of our sequential algorithm on the score provided by our performance test, we found the following properties.

The score depended on the selection of cut-off-frequencies of the bandpass filter, so that in case of noisy recording lower cut-off-frequencies provided better result. On the other hand, low amplitude FQRS signal with low noise favored higher cut-off-frequencies. In addition, bandpass filter with wider bandpass window provided more scattering in the derived FQRS series, when compared the same beats of different signals. However, higher high pass cut-off frequencies filtered out the T wave and prevented QT interval determination. Though a dynamic filter, e.g. Kalman filter, might have solved this problem more efficiently, the use of two different band pass filters to provide twice as many signals for analysis seemed to solve the problem at least partially.

In the construction of the FQRS filters with the purpose to eliminate false positive FQRS peaks of the trigger signal, there were several parameters playing role. One was the size of the reference grid with beats separated by the local mean RR interval used for matching with FQRS peaks. We tested grids with 8, 10 and 12 RR intervals and obtained the best results with 10 intervals. Next, the FQRS error depended on the criteria for the inclusion true beats into the FQRS series and elimination of the false positive beats. The critical values for deviation of a particular peak position from the reference one were set to be smaller than 1/4 of the grid RR interval for the beat to be selected, and smaller than 1/8 of the grid RR interval for not participating in the error. Though these criteria were not extensively tested, it seems that deviations that participate to the physiological RRV are not crucial for the FQRS error, since the smaller squared numbers do not participate to the error so much than bigger ones.

Hence, the most important steps in the derivation of fetal RR series were the construction of a high quality trigger signal providing accurate fiducial points and an algorithm for rejection of false beats and interpolation of missing beats.

Finally, we observed that the best performance score was nearly always provided by the global FQRS series in which we considered all FQRS series with acceptably low FQRS error. However, in roughly less than 10% of recordings, the best score belonged to a lead specific FQRS signal. Moreover, in some cases it was not paralleled in the lowest FQRS error. It suggests that either the algorithm or its criteria for selection of beats is still not optimal.

Acknowledgements

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