Fetal QRS Detection and RR Interval Measurement in Noninvasively Registered Abdominal ECGs

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Abstract

In the context of the CinC-challenge 2013 we present a method for fetal QRS detection in abdominal ECG recordings. Maternal ECG attenuation is based on PQSRT template subtraction and subsequent elimination of the first three principal components. Fetal QRS detection follows a matched filtering approach with an impulse-train filter and a second filter with complementary impulse response. The interspacing of the impulses corresponds to putative fetal RR intervals and is systematically varied, where the relation of both filter outputs permits assessment of the signal-to-noise ratio. In epochs of 1s duration, we use this information to dynamically combine information from an arbitrary number of abdominal channels into a virtual channel, and estimate the local RR interval and initial fetal QRS positions. In a final step these candidate positions are refined using a dynamic programming approach with constraints on SNR, signal amplitude and continuity of RR intervals.

In the test set of 100 4-channel recordings (60s, 1 kHz), we observed good detection accuracy up to moderate SNRs, with an overall RMS-error of 9.35 ms versus reference RR-intervals from scalp recordings.

1. Introduction

The problem of fetal ECG extraction has already been tackled by the pioneers of biomedical signal processing [1, 2]. Meanwhile, many different, partly highly sophisticated signal processing methods have been suggested in the literature [3], even for single channel recordings [4]. A relative appraisal of their merits, strengths and weaknesses is difficult owing to the lack of a common, comparable data base. The CinC-challenge 2013 provides a perfect platform to overcome this situation. In this context, it was our aim to contribute a challenge entry based on rather elementary, robust and well-established signal processing techniques.

2. Methods

The challenge data comprised a learning set of 75 records (a01-a75) where reference fetal QRS (fQRS) positions derived from scalp recordings were revealed, and a test set of 100 records (b00-b99) without any annotations. Each record was 60s in duration and consisted of four abdominal channels sampled at 1 kHz. The challenge tasks were to match the reference fetal RR-intervals (event 5) and the 6s mean heart rate (event 4) as close as possible. Deviations from the reference were assessed as root-mean-square-error between the matching RR-intervals resp. mean-square-error of HR estimates.

2.1. Preprocessing

In order to suppress baseline wander, two different baseline estimates were calculated. First a butterworth low-pass filter at 0.5 Hz. Second, a median filter of width 301 ms. If the difference between both estimates was below a predefined threshold (20 LSB), the linear estimate was subtracted from the ECG, otherwise the median estimate was used.

Mains interference was suppressed by elimination of the maximal spectral component found in the region between 48 Hz and 62 Hz in the Fast Fourier Transform of the baseline-filtered ECG.

2.2. Maternal ECG cancellation

After maternal QRS detection using an adaptive threshold on the energy of the band-pass filtered ECG (8-25Hz, 4th order butterworth), a representative maternal complex [R-300ms;R+800ms] was calculated for each lead and subtracted from the ECG centered at the QRS fiducials. Residual maternal ECG activity was suppressed by eliminating the first three principal components separately in the P [R-300ms;R-100ms], QRS [R-100ms; R+100ms], and T region [R+100ms;R+400ms]. The remaining signal was considered to represent the fetal ECG (fECG) signal plus noise and artefacts.

2.3. Fetal ECG preprocessing

In order to accentuate the fQRS complexes, the fECG was high-pass filtered using a median filter of width 51ms. The effect of high-frequency noise bursts and artefacts was reduced by limiting the magnitudes of each channel to their 99.5% percentile (clipping). Moreover amplitude normalization to unity standard deviation was performed in adjacent non-overlapping segments of 1 sec duration. The result of these steps served as basis for all further fECG processing.

To make better use of the fQRS energy in cases with biphasic fQRS morphologies, we estimated the time-delay between positive and negative QRS half-wave from the autocorrelation-function and added the original to the appropriately delayed and sign-corrected signal.

Similarly, we estimated the time-delay between ascending and descending slope of the fQRS in the differentiated fECG via correlation. The point-wise product of the original differentiated signal and its appropriately aligned and sign-corrected copy served as a supplementary derived channel.

All later steps use the absolute values of the channels as processed up to this point.

2.4. SNR and Rate/QRS-estimation

A crucial idea in our approach is the application of a kind of "matched filtering" (MF) process to obtain estimates of local heart rate, signal-to-noise ratio (SNR), and initial QRS position candidates. In the current step, the primary purpose is to identify relevant channels which contain fetal signals in order to combine them to a single channel for final analysis in the last step.

To this end, we constructed a set of FIR filters where the coefficients consisted of triangular impulse-trains with a predefined interspacing (fig. 1). The interspacing corresponds to the assumed candidate fetal RR (fRR) interval to be tested for. We systematically constructed filters covering 250 ms interspacing up to the 30% quantile of the maternal heart rate (at most 660 ms) in steps of 1 ms. These filters were convolved with each of the pre-processed fECG channels. Additionally, the fECGs were convolved with filters of complementary characteristics (complementary filter, CF), i.e. showing equally interspaced notches in their impulse responses (fig. 1). For both filters MF and CF the coefficients were normalized such that their values accumulate to unity.

Up to moderate SNRs, we expect to observe a maximum in the MF output when the spikes of the filter match the true QRS positions. Note that in this condition, the inter-spike distance reflects the local fRR interval and the IF output quantifies the noise level. The output of the MF normalized point-wise to the sum of the output of both filters, i.e. the MF's instantaneous relative fraction *RF*

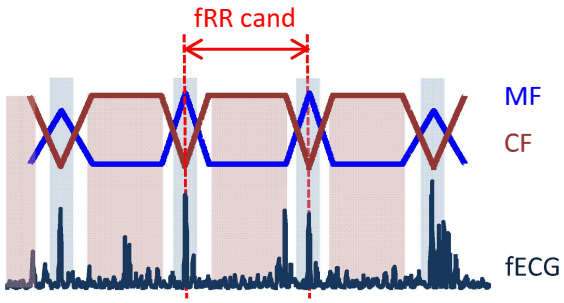

Figure 1 Impulse response of a 4-spike matched impulse-train filter (MF, blue line) and the complementary filter (CF, red line). The blue background color indicates the fECG signal parts interpreted as fQRS signal, whereas components on the red background are considered as noise. When the inter-spike distance matches the true fRR interval, the observed SNR is maximized.

$$RF(t, fRR) = \frac{fECG(t) * MF(fRR)}{fECG(t) * IF(fRR) + fECG(t) * MF(fRR)}$$

can be considered an estimate of the local SNR. Shifting of the filter spikes relative to the fECG will result in fQRS energy counted as noise, and hopefully less energy collected by the MF, i.e. in a reduction of the fraction.

In our further processing, we considered adjacent, non-overlapping epochs of 1s duration, and assessed for each epoch k and each candidate *fRR* interval (i.e. inter-spike distance) the maximum value of *RF* (*MRF*).

$$MRF(k, fRR) = \max_{t \in [k;k+1]\, sec} RF(t, fRR)$$

A critical assumption is that we expect an absolute or at least relatively high local maximum in MRF for the specific spike-interspacing that matches the true local fRR-interval of a given epoch k (fig .3).

To identify the fetal heart rate for each epoch, we realized a dynamic programming algorithm which identifies a temporally ordered path $\{k, fRR^*(k)\}$ across the 'MRF time/heart-interval plane' that aims to maximize the MRF values on the path and at the same time penalizes abrupt RR fluctuations from one epoch to the next. Fig 3 shows an example of the result of this step.

Finally, candidate positions for the QRSs were derived by assuming a QRS at the position of the maximum $RF(t, fRR^*(k))$ within each 1 sec epoch, and complementing the epoch with further positions in the distance of the local RR estimate.

In our final realization we used two filters with a number of 4 and of 10 impulses, and added the convolution fractions element-wise (implying a maximum value of 2, cf. fig. 2). The width of the triangular impulses was reduced linearly from 200 ms for the "outer" impulses to 100 ms for the "inner". Similarly, the amplitude was weighted inversely to the width giving more emphasis to the central pulses and permitting greater heart rate fluctuations for the more distant spikes.

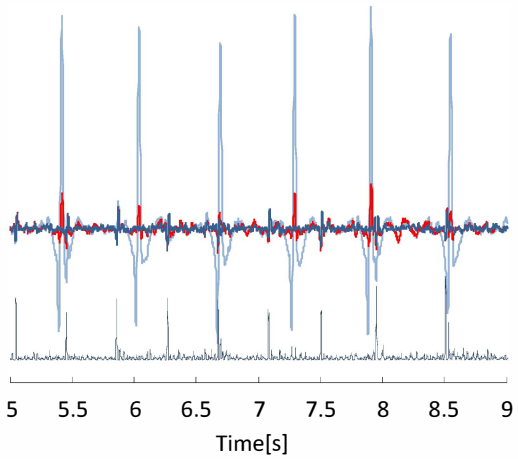

Figure 2. Maternal ECG cancellation. The upper traces show the maternal ECG after baseline correction and mains filtering (light blue), template subtraction (red) and elimination of the first three principal components (dark blue). The lower trace shows the final combined virtual fECG channel (record b79).

2.5. Channel selection and channel combination

The final detection of fetal QRS complexes is performed on a "virtual" signal channel that is derived by merging data from the various channels according to their SNR as estimated in the previous step. To prevent entirely noisy channels from corrupting this combined signal, we checked values of the convolution ratio at the candidate positions. Only channels with the 20% quantile of $MRF(k, fRR^*(k))$ exceeding the empirically set value of 1.2 were eligible to contribute to the combination.

Acceptable channels were combined by weighted summation in adjacent non-overlapping epochs of 1 sec duration. The weights were determined individually for each epoch and were proportional to a channel's maximum SNR value for that epoch. Normalization guaranteed that all weights summed to one.

2.6. Fetal QRS candidate estimation

The same impulse-train filtering process as described in section 2.4 was used to estimate the 'final' candidate QRS positions from the combined virtual channel. In a last step, those candidate estimates were refined.

2.7. Fetal QRS refinement

For each fQRS candidate, we identified a set of 5 potential alternatives in its vicinity (±100 ms) as the highest local maxima of the combined fECG channel. Similar to the estimation of the local fRR in step 2.4, we used a dynamic programming algorithm, to identify an optimal path traversing the alternatives which maximized

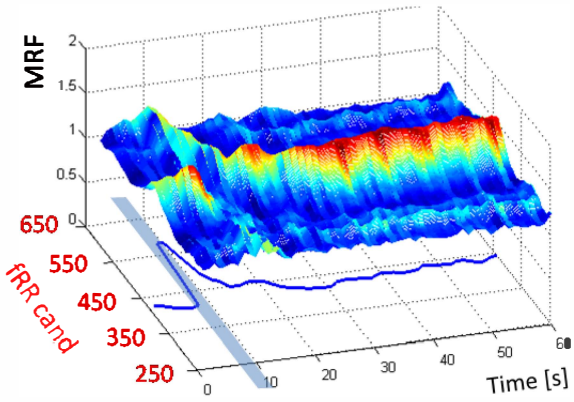

Figure 3. Epoch maxima $MRF(k, fRR)$ over the 'time/candidate-fRR plane (record b79). The blue line at the base of the figure indicates the identified optimal path $\{k, fRR^*(k)\}$ following the SNR 'ridge'. The corresponding candidate fRR intervals are assumed to reflect the true local fRR intervals.

the amplitudes of the virtual combined channel $fECG_{virt}(t_{cand})$ and of $RF(t_{cand}, fRR^*(k))$, i.e. the SNR, and penalized abrupt RR fluctuations.

A final step tested for deletion of fQRS candidates in case that the overall signal quality was good and the candidates had very low fECG amplitudes and relatively low SNR, and implied an abrupt decrease of the fRR interval by more than 40ms.

3. Results

Figure 2 shows the result of the maternal ECG cancellation as described in section 2.2. Here, the PCA is able to suppress remaining maternal QRS activity after template subtraction (red line) without significant degradation of the fetal QRS even in case of coincident QRSs. The final virtual fECG channel derived by combination of channels 2, 3 and 4 is free from maternal ECG activity. Figure 3 shows the epoch maxima $MRF(k, fRR)$ of the relative fraction of the matched filter output in a case

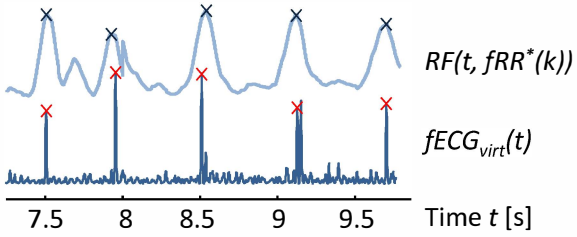

Figure 4. Refinement of the fQRS candidate positions (blue crosses) as identified in $RF(t, fRR^*(k))$ (upper trace) by constrained selection among alternatives of local maxima in the virtual combined channel $fECG_{virt}(t)$ (lower trace). The red crosses indicate the final fQRS positions. The time segment corresponds to the steep increase in fRR indicated in fig. 2 (record b79).

with a severe abrupt increase of fRR by more than 150 ms at t = 8s. Still, the clearly pronounced ridge permits to trace the correct local fRR interval and provide meaningful fQRS candidate positions. Figure 4 illustrates the refinement step for the fQRS candidates.

Our best scores achieved on the test set b were a RMS error for matched fRR-intervals of 9.35 ms (event 5), and a MSQ error of 118 bpm^2 for the mean heart rate (evnt 4).

4. Discussion

We have proposed a successful approach for fetal QRS detection and RR interval measurement based on elementary and well traceable signal processing methods. The method combines information from an arbitrary number of abdominal channels, but can work already with a single-lead registration, and tolerates dynamic loss of channels. The results show good detection accuracy up to a moderate SNR of the fECG, but there were clear problems in case of very low-SNR fECGs. We attribute these problems to two main reasons: to a lesser part to limitations of our maternal ECG attenuation method, and to a larger extent to the critical role of the initial fetal RR candidate selection (section 2.4) and constriction.

A prerequisite for its successful elimination in our realization is that the maternal ECG signal is sufficiently clearly detectable and free from ventricular ectopy (although the less steep signal fluctuations in ventricular beats may not critically interfere with the fetal ECG). Our approach appeared robust against maternal supraventricular ectopy. But in few cases the maternal QRS complexes were not properly identified, and consequently insufficiently attenuated (resp. artificially introduced by inappropriate template subtraction in a wrong position). A point that may also have had negative influence in few cases is the occasional attenuation of fQRSs by the PCA step. But the subsequent convolution with the impulse-train filter will likely compensate for that since a candidate fQRS still will be placed appropriately.

The most critical step in our approach is the selection of the correct instantaneous fetal RR interval. Dependent on this choice, the candidate positions for the fQRS are placed and refined. Errors in this step are hard to identify and correct during later processing. The properties of the algorithm tracing the optimal route through the 'time/heart-rate plane' (e. g. with respect to penalization of heart rate fluctuations) are crucial for its performance, particularly in cases with bad SNR, where spurious artifact-related local maxima occur.

Equally, the number and the width of the spikes in the matched filter are important parameters. A large number of impulses will be able to better bridge noisy data segments but will imply a more or less constant heart rate assumption. A smaller number of impulses will be less robust against noise but will show smaller bias in case of significant heart rate changes. Figs. 3 and 4 demonstrate that the algorithm and the final refinement step are able to track the correct fRR even in the face of strong abrupt changes as long as the SNR is acceptable. This was observed also for ectopics or pauses.

Unfortunately we were not able to invest the time for systematic optimization of the various parameter settings but had to work with initial 'gut feeling' values. But we feel that this point holds potential for significant performance improvement in cases with bad signal quality.

One of the strengths of our method is the availability of a dynamic SNR estimate which can be interpreted as a 'degree of evidence' for the proposed fQRS candidates. This is also the key information used for the identification and combination of channels that contribute to the finally used virtual channel.

In future extensions, the SNR information should also be used to guide the selection of parameters adaptively, e.g. increase the number of impulses in the matched filter or invoke stronger filtering in case of bad SNR. Also for the refinement of the fQRS positions, this information appears very valuable and has only been exploited rudimentarily in our approach. Moreover, information on the expected heart rate range could be gathered from reliably identifiable signal sections, and used to constrain the search range for candidate intervals to plausible values in sections with bad SNR.

Finally, we see an interesting option for sensor fusion in our approach: It would be straightforward to include complementary information from independent sources like cardiotocography, e.g. to guide the critical fRR initialization or constriction.

References

[1] van Bemmel JH, van der Weide H. Detection procedure to represent the foetal heart rate and electrocardiogram. IEEE Trans Biomed Eng 1966 Oct;13(4):175–182.

[2] Cerutti S, Baselli G, Civardi S, Ferrazzi E, Marconi AM, Pagani M, et al. Variability analysis of fetal heart rate signals as obtained from abdominal electrocardiographic recordings. J Perinat Med 1986;14(6):445–452.

[3] Sameni R, Clifford GD. A Review of Fetal ECG Signal Processing; Issues and Promising Directions. Open Pacing Electrophysiol Ther J. 2010 Jan;3:4–20.

[4] Niknazar M, Rivet B, Jutten C. Fetal ECG extraction by extended state Kalman filtering based on single-channel recordings. IEEE Trans Biomed Eng. 2013 ;60:1345–1352.

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