Maternal Signal Estimation by Kalman Filtering and Template Adaptation for Fetal Heart Rate Extraction

Fernando Andreotti[1], Maik Riedl[2], Tilo Himmelsbach[1], Daniel Wedekind[1],
Sebastian Zaunseder[1], Niels Wessel[2], Hagen Malberg[1]

[1] Technische Universität Dresden / Institute of Biomedical Engineering, Dresden, Germany
[2] Humboldt-Universität zu Berlin / Cardiovascular Physics, Berlin, Germany

Abstract

The fetal ECG derived from abdominal leads is an interesting alternative to standard fetal heart monitoring methods. Due to the temporal and spectral overlap of maternal and fetal signals, the usage of abdominal leads requires elaborated signal processing routines. In this work a modular combination of processing techniques is presented. The core of the evaluated scheme consists of two maternal ECG estimation techniques, namely the Extended Kalman Smoother (EKS) and Template Adaption (TA). Different method combinations are compared using the Computing in Cardiology Challenge 2013's scoring system. The obtained results prove that the proposed methods produce reliable fetal heart rate estimates. For training Set-A we obtained scores of 9.90/2.98 (Event 4/5) for TA, 196/6.78 for EKS and 15.7/3.25 combined versions of each method. For Set-B the best scores (18.1/4.38) were produced by TA in combination with statistical postprocessing.

1. Introduction

Standard techniques for fetal heart rate monitoring are either invasive (fetal scalp electrode) or have high false-positive rates concerning heart rate changes (Doppler ultrasound), aside from not being suited for long-term measurements [1]. Due to its versatility the fetal ECG derived from abdominal leads is a promising alternative to standard techniques. Although many studies contemplated the topic, extraction (i.e. maternal interference estimation and cancellation) along with trustworthy fetal QRS detection still is a difficult task. Many factors contribute to this, e.g. the varying (and usually low) fetal signal-to-noise ratio, temporal and spectral overlap of fetal and maternal ECG signals and the morphological similarity between QRS complexes of mother and fetus.

Many extraction methods have been proposed in literature to overcome the existing problems. Thereby temporal extraction methods are widely used. This work presents the further development of [2] which compared methods for maternal ECG estimation, namely the Extended Kalman Smoother (EKS) [3] and the Event Synchronous Canceller [4]. For this contribution the latter method was further developed to allow a more flexible fitting of maternal templates, here referred to as Template Adaptation (TA). EKS and TA are combined with a newly developed QRS detector and postprocessing scheme in order to extract the fetal ECG and derive the fetal heart rate.

2. Methodology

As different processing methods are combined and compared, a modular signal processing scheme (see Fig. 1) was implemented. The signal processing blocks shown in Fig. 1 are interchangeable and often composed of several subroutines. In the following subsections, each individual block is explained.

2.1. Preprocessing

Preprocessing is intended to reduce baseline wander, muscular artifacts and power-line interference. The first two interferences are reduced with a bandpass between 3-80 Hz. For power-line removal two notch-filters at 50 Hz and 60 Hz are applied, since the origin of the data is unknown. Filtering is done by applying 1000 taps cascaded FIR filters, which are used in forward and backward direction to perform zero-phase filtering.

2.2. Maternal QRS detection

In order to detect maternal QRS complexes (mQRS), the maternal signal is firstly enhanced by using spatial filtering. Afterwards the mQRS morphology is exploited for a matched filter detection approach.

Regarding the maternal signal enhancement, Independent Component Analysis (ICA) which was previously proposed for separating fetal and maternal ECG components [5] is used. In this study, the FastICA algorithm is ap-

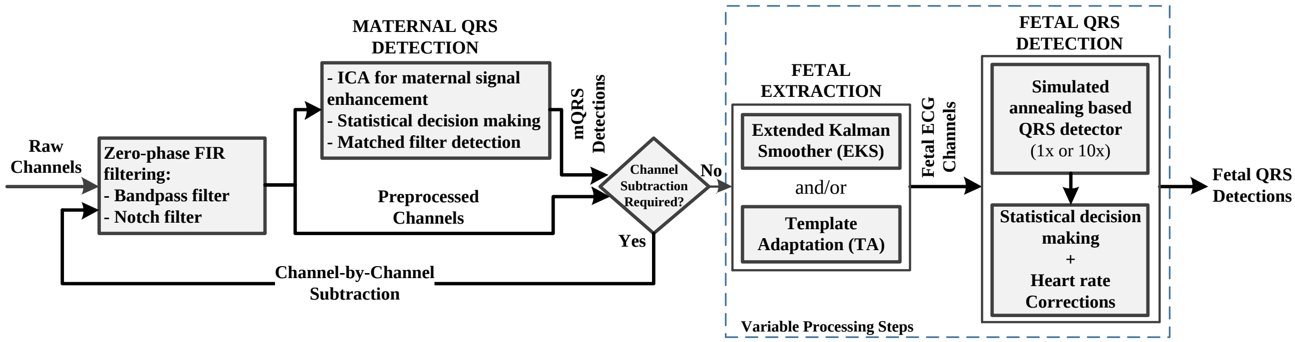

Figure 1. General scheme describing signal processing chain. The dotted line emphasizes the processing steps which are differently combined establishing the trials outlined in section 2.6.

plied on the preprocessed channels, incorporating whitening and making use of a hyperbolic tangent measurement function (as suggested by Hyvärinen [6]).

To select the component with predominant maternal signal, mQRS detection is performed in each of the preprocessed channels (primary QRS detection) and in all ICA's output channels (secondary QRS detection). The channel-based detections are weighted according to the likeness between primary and secondary QRS detections (high likeness is assumed to indicate a suitable output channel). The chosen channel is then subjected to the statistical decision-making procedure (explained in section 2.5). Based on the statistical decision's output, a maternal template beat is generated and used to detect maternal QRS complexes in the channel with highest likeness by a matched filter approach.

By exploiting the amplitude of found mQRS complexes, channels are subtracted from each other in case of large mQRS amplitudes. This property was assumed to be indicative of unipolar measurements which benefit from this subtraction. The resulting six channels are than preprocessed and concurrently used with the four pre-existing leads for further processing (see Fig. 1).

2.3. Fetal signal extraction

As already mentioned, fetal signal extraction is done by maternal ECG estimation in each channel, followed by subtraction from the preprocessed channels. The proposed methods (EKS and TA) have similar structures but differing maternal ECG modelling.

2.3.1. Maternal estimation by means of extended Kalman smoother

The Kalman Filter is a promising and very versatile framework for fetal ECG extraction proposed by Sameni et. al. [3]. Its extension for non-linear systems (namely Extended Kalman Filter) followed by a backward smoothing stage (EKS) provides a trustworthy estimation for maternal ECG projection within abdominal leads. The estimation is based on a system model which approximates an average maternal beat, obtained by wrapping the single beats, with Gaussian kernels [3]. The Kalman gain is then used to correct on a sample basis the observed signals considering the modeled system dynamics and present noise disturbances in order to produce plausible estimations.

2.3.2. Maternal estimation by means of template adaptation

TA is an approach which makes use of similar ideas as the Event-Synchronous Canceller (ESC) [4]. It uses an average maternal beat (wrapped template) and adapts it directly back to the original signal without any fixed mathematical modelling. Differently from ESC, TA also allows a width adaption (stretching), granting TA more flexibility. For its adaptation the template is segmented within three parts (Q, R and S waves). These segments are allowed to vary in width and height, which gives the extraction method some additional degrees of freedom. However, based on the signal trend a constraint on the height of the templates is made in order to avoid complete cancellation of fetal peaks in cases of complete overlap.

2.4. Fetal QRS detection

For detecting fetal QRS (fQRS), a detector based on two basic principles, namely the beat morphology and the overall beat-to-beat interval consistency of the recording, was developed.

The detector treats each detection as an independent object which may exist, move or cease existence. The manipulation of detections is interpreted as an optimization problem. The optimization aims at minimizing a cost function which evaluates the afore mentioned principles (morphology and beat-to-beat consistency) over each iteration, i.e. each manipulation of a single detection. In order to mini-

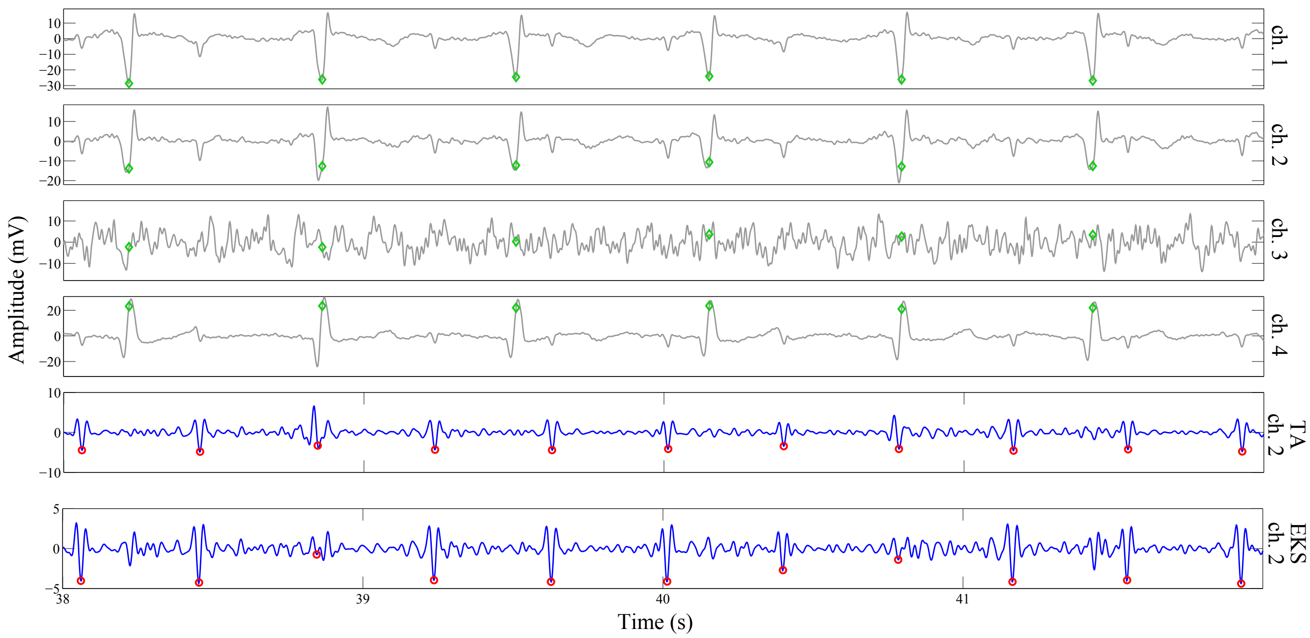

Figure 2. Comparison between TA and EKS extractions for test data b01. First 4 plots show the preprocessed channels, plots 5 and 6 show respectively extracted signals using TA and EKS. Detections are represented by ◇ (mQRS) and ○ (fQRS)

mize the global cost function, Simulated Annealing [7] is used to derive fQRS annotations for each channel. After detecting viable fQRS within each channel, the detector uses the channels which are considered to be most trustworthy to generate a set of multichannel detections. Since the optimization is affected by its chosen process variables, the procedure might get stuck in local optima or not converge producing random differences in its results.

2.5. Decision-making and correction

The resulting fQRS detections still need to be synthesized in one consensus detection. Whilst constructing this consensus, false-positive and false-negative detections are taken into account by using kernel estimation of the peaks' distributions in multiple channels [8]. Normalized (to an amplitude of 1) Gaussian kernel functions with 30 ms standard deviation are centered at the time instants of each detected peak. The sum of these kernels results in a distribution of peaks which range from zero to the number of considered channels. The height of the local maxima represent the match of detections in multiple channels. Values over a threshold (half of the channel number) are accepted as fetal QRS complexes. The lower local maximum of two accepted neighbors is deleted if both have a temporal distance which is smaller than a defined threshold (300 ms). Last, the accepted local maxima are corrected for plausible fetal heart rates, by adding peaks at the borders of gaps and exchanging peaks to decrease heart rate variability in consideration of the all local maxima.

Finally, sudden heart rates jumps greater than 70 ms are removed and still existing gaps are filled without distribution information.

2.6. Combination of processing methods

The two estimation methods, together with the decision making and correction, allow different combinations of processing techniques (trials). Trials were carried for training Set-A, which was also manually corrected for some missing/inaccurate annotations (resulting in Set-A_c), as well as, for test Set-B.

First, the extraction methods were individually tested (Trial 1 and 2) using the described scheme. Second, the detections produced by the fQRS detector for both EKS and TA methods were put together and served as input for the decision procedure (Trial 3). Due to the stochasticity of the optimization process used by the fQRS detector, it produces non-deterministic results. Exploting the ideas of ensemble techniques [9] the detector was repeatedly used 10 times for both TA (Trial 4) and EKS (Trial 5). Finally, due to the different behaviours of EKS and TA, a criterion was created to automatically choose between which of the extraction methods to use for each record (Trial 6), based on how much the absolute number of fQRS detections vary within the ten available detections.

3. Results

Tab. 1 shows the average scores obtained for each trial (zero means perfect detection). Fig. 2 depicts exemplary preprocessed data for each of the four available channels, together with extracted results from second channel.

Table 1. Scores obtained for training and test sets (n.a. - not available). Scores are shown as (Event 4/ Event 5).

Trial	Set-A	Set-A_c	Set-B
1 TA	9.90/2.98	5.55/1.15	20.4/4.57
2 EKS	196/6.78	191/4.91	219/7.69
3 TA+EKS	15.7/3.25	11.4/1.42	140/6.88
4 10x TA	9.74/2.95	5.31/1.12	18.1/4.38
5 10x EKS	324/9.06	320/7.25	n.a.
6 10x TA/EKS	9.83/2.93	5.47/1.10	43.5/4.88

4. Discussion

Compared to the reference implementation (available on: *http://physionet.org/challenge/2013/*) which obtained 2696/102.0 (Set-A) and 2684/101.4 (Set-A_c), there is a clear improvement (Tab. 1). Both extraction methods perform well in Event 5 (RMS of fetal RR) and are able to produce reliable fQRS detections. However, EKS performs distinctly worse on Event 4 (MSE of fetal heart rate). A removal of overlapping beats and attempt to correct missing beats might be responsible for results' degradation. Fig. 2 illustrates that TA avoids complete cancellation of the fetal peaks in cases of complete feto-maternal overlap. Although for EKS some fetal peaks are missing (e.g. before 39 and 41 s) the detections seem accurate due to the corrections made during the decision making procedure.

Considering overall scores, TA outperforms EKS. TA is able to generate better estimates for the maternal interference, leaving easily detectable fQRS complexes. By detecting each dataset multiple times, the intrinsic stochasticity of the detector is minimized for TA (trials 1/4), but results degrade for EKS (trials 2/5).

Even though TA produces more reliable scores, EKS is a method which has potential for further developments. The fact was proven e.g. on the record 71 (Set-A), on which TA failed to provide a good estimation but EKS could. Regarding such developments, a different modelling using EKS might be used. First tests have shown promising results using adaptive noise modelling. Furthermore, asymmetrical distribution kernels or even more accurate phase information might prevent fetal peaks to cross out and allow better estimates.

5. Conclusion

In the actual state, Template Adaptation delivers the best results. Despite that, EKS still has many degrees of freedom and for further studies the combination of both TA and EKS holds great potential to improve our results due to the differing behaviours of the proposed estimation techniques.

Acknowledgements

The authors thank the CNPq (Conselho Nacional de Desenvolvimento Tecnológico - Brazil) and the DFG (Deutsche Forschungsgemeinschaft - RI2016/2-1) for financial support.

References

[1] Karvounis EC, Tsipouras MG, Fotiadis DI, Naka KK. An Automated Methodology for Fetal Heart Rate Extraction From the Abdominal Electrocardiogram. IEEE JITBM November 2007;11(6):628–638. ISSN 1089-7771.

[2] Zaunseder S, Andreotti F, Cruz M, Stepan H, Schmieder C, Malberg H, Jank A, Wessel N. Fetal QRS Detection by means of Kalman Filtering and using the Event Synchronous Canceller. In International Journal of Bioelectromagnetism. ISSN 1456-7865; 83–89.

[3] Sameni R, Shamsollahi MB, Jutten C. Filtering Electrocardiogram Signals Using the Extended Kalman Filter. In IEEE–EMBS. 2005; 5639–5642.

[4] Ungureanu M, Wolf WM. Basic Aspects Concerning the Event-Synchronous Interference Canceller. IEEE JBME 2006;53(11):2240–2247.

[5] Castells F, Cebrián A, Millet J. The role of independent component analysis in the signal processing of ECG recordings. Biomedizinische Technik Biomedical engineering February 2007;52(1):18–24. ISSN 0013-5585.

[6] Hyvärinen A. Fast and robust fixed-point algorithms for independent component analysis. IEEE Transactions on Neural Networks January 1999;10(3):626–34. ISSN 1045-9227.

[7] Kirkpatrick S, Gelatt CD, Vecchi MP. Optimization by simulated annealing. Science New York NY May 1983; 220(4598):671–80. ISSN 0036-8075.

[8] Silverman BW. Density estimation for statistics and data analysis. Chapman & Hall/CRC, 1986.

[9] Polikar R. Ensemble based systems in decision making. IEEE Circuits and Systems Magazine 2006;6(3):21–45. ISSN 1531-636X.

Address for correspondence:

Fernando Andreotti
TU Dresden - Institut für Biomedizinische Technik
Helmholzstr. 10
01069 Dresden
fernando.andreotti@mailbox.tu-dresden.de