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Fetal QRS Detection by means of Kalman Filtering and using the Event Synchronous Canceller

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Abstract. The fetal ECG (fECG) provides a mean to monitor non-invasively the fetal heart activity. Until today, its low signal to noise ratio hampered an extended use of the fECG in clinical practice. As proposed processing methods have shown a lack of accuracy in certain circumstances, the characterization and further development of methods to process the fECG is of high interest. This contribution aims at a comparative evaluation of two methods, namely a Kalman Filter based approach and a classical template subtraction approach, regarding their ability to be used in the context of fetal QRS detection. Although both methods prove to be applicable to detect fetal QRS complexes, the Kalman based approach has shown to perform more accurately using simulated and real datasets.

Keywords Abdominal recording; Event Synchronous Canceller; Fetal ECG ; Kalman Filter; Template Subtraction

1. Introduction

Cardiotocography (CTG) is a common procedure to assess the fetal health [Stout and Cahill, 2011]. By using ultrasounds, CTG provides a mean to analyze the fetal heart rate (fHR). At the same time, uterine activity is recorded by a pressure transducer. CTG has proven its diagnostic value in many cases, making the technology an indispensable tool in the obstetric field.

In spite of its clinical importance, regarding the fetal heart CTG only provides information on the mechanics. Further on, CTG allows only intermittent short-term recordings which have to be performed under expert guidance. The fetal ECG (fECG) constitutes an alternative to derive statements about the fetal heart. The fECG can be recorded invasively (typically by using a scalp electrode) but also non-invasive recordings are feasible by magnetocardiography or by placing electrodes on the mother's abdomen. The latter approach, so called abdominal recording, is of high interest as this technique provides an exceptionally facile mean to continuously record the fECG. Besides the analysis of the fHR, application scenarios which rely upon a fECG comprise the analysis of fetal heart rate variability (fHRV) [Van Leeuwen et al., 2007], the analysis of fetal-maternal synchronization [Riedl et al., 2009] and the morphological analysis of the fECG [Clifford et al., 2011] in stationary and even ambulatory settings. Due to its explanatory power as well as its superior application conditions, the fECG acquired from abdominal electrodes has the potential to significantly supplement, or in some cases even substitute, the CTG in obstetric diagnostics.

In today's clinical practice, however, the fECG usage is almost completely limited to the heart-beat analysis and invasive ECG recordings (measured by a scalp electrode during labor). An expanded use of the fECG measured by electrodes placed on the maternal abdomen is hindered by the low SNR of the fECG. So far, the technology to reliably measure fECG is largely still unavailable [Sameni, 2008].

Recently, many approaches have been proposed to process the fECG. The most crucial issue in processing abdominal recordings remains the extraction of the fECG, i.e. the separation of the fetal signal components from noise sources, most importantly the maternal ECG (mECG). Due to the time and spectral overlap between maternal and fetal ECG signals, the extraction process requires specific processing methods. Martens [Martens, 2003] categorizes the different procedures in three groups: temporal, spatial and the so called spatio-temporal methods, a combination of the aforementioned ones.

Temporal methods make use of the time-uncorrelation and pseudo-periodicity of both fECG and mECG. Methods such as the Event Synchronous Interference Canceller (ESC) [Ungureanu and Wolf, 2006], Kalman Filter (KF) [Sameni et al., 2005] and Linear Prediction [Vullings et al., 2009] are used in order to generate an estimation of mECG which is subtracted from the abdominal ECG.

Spatial methods on the other hand attempt to separate the fetal signal by using information on the spatial distribution of the source signals ensemble. Independent Component Analysis (ICA) [Lathauwer et al., 2000], Principal Component Analysis (PCA) [Martens, 2003], Singular Value Decomposition (SVD) [Ayat et al., 2008] and Nonlinear State-Space Projections (NSSP) [Richter et al., 1998] are exploited within this scope. At last, the combined procedures (spatio-temporal methods) are sequential or joint applications of both former described techniques, e.g. [Kotas et al., 2011].

Although spatial techniques are widely used, they usually require a large number of channels. Meanwhile for a small number of electrodes it has been proven [Kotas et al., 2008] that temporal techniques show better results. Keeping in mind that mother's comfort during recordings is a crucial aspect, a small number of channels is preferred.

The present study therefore aims at evaluating the applicability of two temporal methods, namely KF and the ESC, in the context of fetal QRS detection. Both methods, KF and ESC, can be applied to single channel abdominal recordings and are thought to be able to preserve the morphology of the fECG during its extraction. These characteristics render those methods promising choices and contribute to the interest in their development and deeper characterization.

2. Material and Methods

2.1. Data material

Consideration regarding the data to be used

In this study we consider both, real and simulated data. The usage of simulated data provides the advantage of knowing about the occurrence of fetal QRS complexes. Thus it is possible to draw conclusions on the usability of a fetal QRS detection method as a function of known boundary conditions (i.e. a fECG is existent at a certain fetal-maternal SNR). Particularly when no interactions between channels are exploited the usage of simulated data may provide meaningful results on a detection method's efficiency in a theoretical way. Real data is necessary to validate the relevance of the theoretical findings into the real world.

Simulated Data

Simulated data was created by superimposing records of the Normal Sinus Rhythm Database (NSRDB) available via PhysioNet [Goldberger et al., 2000]. By using PhysioNet's *xform()* the records were upsampled to 500 Hz and 1000 Hz to represent the fetal and the maternal component, respectively. Different fetal-maternal SNRs were obtained by scaling the amplitude of the fetal signal. Thereto, similar to the proceeding in the field of noise stress testing, the fetal-maternal SNR was derived on the basis of QRS amplitudes, i.e.

$$SNR_{fm} = 10 \cdot \log\left(\frac{P_f}{P_m}\right) \xrightarrow{yields} 10 \cdot \log\left(\frac{amp_f^2}{amp_m^2}\right) \tag{1}$$

where P_f and P_m are the powers of fetal and maternal ECG, respectively. As surrogates of those powers the amplitudes amp_f and amp_m of the QRS complexes as measured by PhysioNet's *sigamp()* function were used. The scaling factor *s*, to be applied in order to guarantee a certain fetal-maternal SNR, was than calculated by

$$s = \frac{amp_f^{desired}}{amp_f} = |amp_m| \cdot \frac{10^{\frac{SNR_{fm}}{20}}}{amp_f} \tag{2}$$

Table 1 contains the identifiers (ID) of the simulated datasets and their original recordings. Each of the superimposed records has a length of 30 minutes (the first 30 for the maternal component and 60 minutes for the fetal component of the respective original records). Evaluated SNRs comprise -3 dB, -6 dB, -9 dB and -12 dB (see Fig. 1) resulting in 36 records overall.

Table 1. Overview on the simulated datasets and the NSRDB records from which the datasets were built up.

Record ID	Maternal ECG	Fetal ECG	Record ID	Maternal ECG	Fetal ECG
1	17052	16265	6	19090	16539
2	17453	16272	7	19093	16773
3	18177	16273	8	19140	16786
4	18184	16420	9	19830	16795
5	19088	16483			

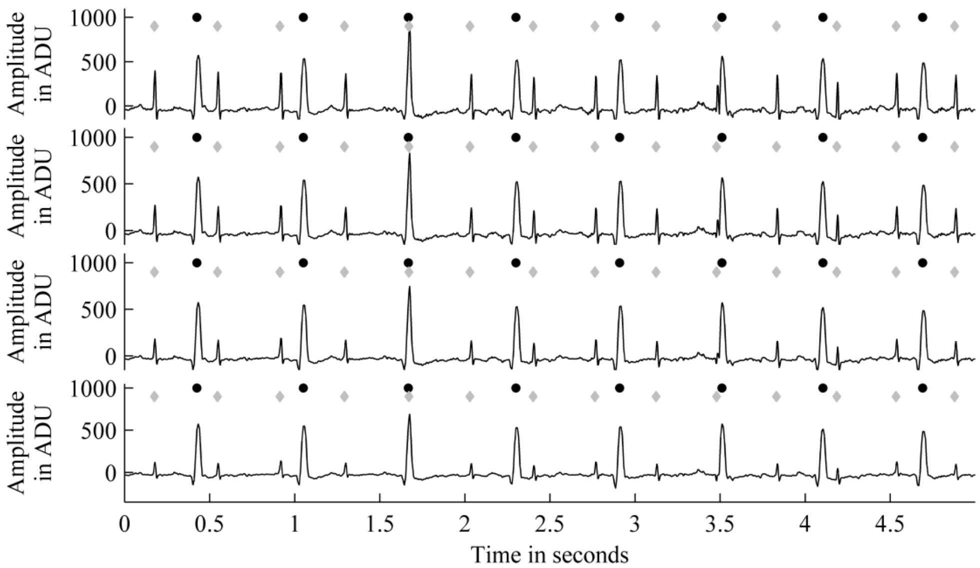

Figure 1. *Signal excerpt of the simulated data (record 1). Top-down fetal-maternal SNRs of -3 dB, -6 dB,-9 dB and -12 dB are shown. Maternal and fetal QRS complexes are marked by black circles and gray diamonds, respectively.*

Real Data

Real data was recorded at the Department of Obstetrics and Gynecology (University of Leipzig). Recordings were carried out using the ADInstruments ML138 Octal Bio Amp and the ADInstruments PowerLab 16/30. Fig. 2 shows the lead configuration which was used. All abdominal channels were analogously filtered by a mains filter and a high pass filter (cutoff frequency 1 Hz). Sampling was done at 1000 Hz. The measurement range of the abdominal recordings was 500 µV.

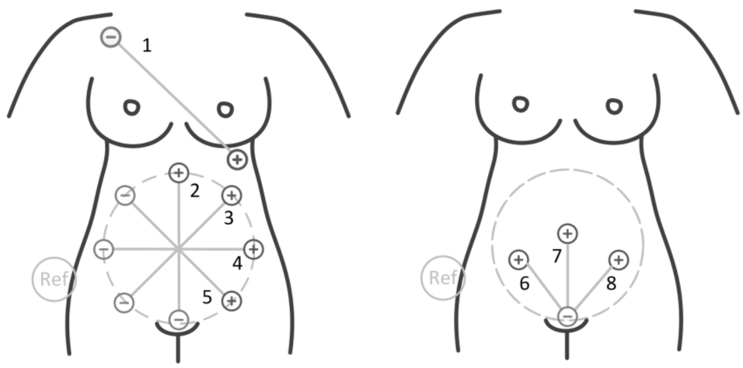

Figure 2. *Lead configuration used to record real data (note that two figures are used only for the clearness of the graphical illustration).*

Within this study, ten datasets from 6 women (aging 29.5 ± 4.4 years, at 27.1 ± 4.4 gestational weeks; all values given by mean ± standard deviation) were evaluated. The datasets were selected manually from a larger patient group to reflect a representative cross-section of occurring signal qualities. Since the interest is in assessing the performance of fetal QRS detection, all selected records show fetal ECG traces. However, fetal-maternal SNRs as well as fetal to noise SNRs are partially very low. Each dataset has duration of 20 minutes. The records were annotated manually by using the maternal channel and two abdominal channels. The two abdominal channels were selected so that the fetal QRS showed differing polarities. Each fetal QRS complex, which was visible using the contextual information of all three channels, was annotated. For automatic processing, a single channel was chosen manually. The chosen channel was the one which exhibits the best quality of fECG as could be observed by visual inspection (twice channel 4, twice channel 5, four times channel 6 and twice channel 7).

2.2. Data Processing

The signal processing comprises the steps which are outlined in Fig. 3. The pursued approaches only differ in the way the extraction of the fECG is handled, more precisely regarding the aspect how the mECG to be subtracted is estimated.

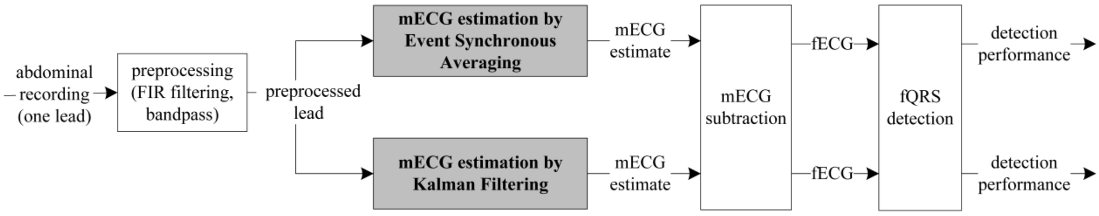

Figure 3. *Applied processing scheme.*

Preprocessing

Preprocessing included the application of a band-pass filter. As only QRS detection was to be accomplished (no morphological evaluation) a pass-band from 2 Hz to 100 Hz was chosen. Filtering was done in forward and reverse direction by applying a 1000 tap FIR filter. To suppress power-line interference an additional FIR filter at power-line frequency was applied.

fECG Extraction - Kalman approach

Kalman Filtering is a recursive data processing algorithm which is ruled by the following state-space equations

$$\begin{aligned} x_k &= \boldsymbol{A}x_{k-1} + \boldsymbol{B}u_{k-1} + w_{k-1} \\ z_k &= \boldsymbol{H}x_k + v_k \end{aligned} \tag{3}$$

Being x_k the desired hidden state, u_k a known input vector and z_k the measurement itself. The random variables, w_k and v_k, describe the stochastic noises associated with the process and observations, respectively. The remaining matrices, namely A (state transition), B (control) and H (observation), model the system dynamics. KF execution relies on two factors: the observation equations and its inner model. Depending on how reliable these factors are, the filter will put more weight on one or the other.

In this study, the Extended Kalman Smoother (EKS), which is an extension of KF, was selected. EKS based filtering is able to extract the maternal ECG component which can be removed afterwards from the composed signal. As dynamic model McSharry's *synthetic ECG generator* was used as modified by Sameni [Sameni, 2008]. In order to construct the model, a phase wrapping of the beats from segments of 200 s in a sliding window was carried out.

fECG Extraction - Event Synchronous Canceller

ESC is based on coherent averaging of N beats to construct a time varying beat template. By subtracting scaled versions of the current template the maternal component is removed from the composed signal. Details on the method can be found in [Ungureanu and Wolf, 2006]. In a previous study different N were tested, the best results corresponded to $N=15$. Alignment of beats was done by maximizing the correlation of each beat compared to one reference beat. To account for differing lengths of the beats Gaussian noise was concatenated to signal excerpts when necessary. In order to build up a signal to be subtracted from the abdominal recording smooth concatenation of scaled versions of the template was applied.

Fetal QRS Detection

QRS detection was performed by two independent algorithms. Firstly, the method proposed by Suhrbier et al. [Suhrbier et al., 2006] was used (here referred to as "QRS detection method 1"). The algorithm searches for relevant slopes by applying a patient adaptive threshold. Secondly, we used a QRS detector based on search for maximal value within a moving window described by Sameni [Sameni, 2008] - (here referred to as "QRS detection method 2").

2.3. Performance assessment

The performance of the processing methods was evaluated in terms of QRS detection performance by using standardized beat-to-beat comparison as provided by PhysioNet's *bxb()* function. According to the ANSI/AAMI EC57:1998 [ANSI/AAMI, 1998] sensitivity *Se* and positive predictive value $+P$ were calculated by

$$Se = \frac{TP}{TP+FN} \qquad\qquad +P = \frac{TP}{TP+FP} \tag{4}$$

where *TP*, *FN* and *FP* are the true positive, false negative and false positive detections, respectively. Compared to the assessment of QRS detectors as depicted in EC57:1998, the temporal match in which a detection was regarded as correct was lowered to 50 ms in order to account for the higher fetal heart rates.

3. Results

Table 2 shows the averaged results for the simulated data at different SNRs. Owing to the handling of the adaptive threshold which is used to extract the relevant slopes, the design of QRS detector 1 guarantees a high positive predictive value. Meanwhile, in case of the KF based approach the sensitivity is only slightly affected by lower fetal-maternal SNRs. Regarding the ESC, the effect is much more pronounced. QRS detector 2 guarantees a more balanced detection performance in which the Kalman approach outperforms ESC. When comparing all combinations it turns out, that the Kalman based approach in combination with QRS detection 2 guarantees the best tradeoff between sensitivity and positive predictive value in three out of four simulated cases.

The detection rates for real data confirm the observed tendency. The decrease in the overall detection rates is owing to the increased influence of additional noise sources which affect the abdominal signals apart from the mECG. Most importantly this pertains to muscular noise which overlaps the spectrum of the fECG considerably.

Table 2. *Average results for the test data (results in %; the best tradeoff between +P and Se in terms of the maximum arithmetic mean of both quantities is shadowed for each testing set).*

Test set	*Kalman*		*ESC*		*Kalman*		*ESC*	
	QRS detction method 1				*QRS detction method 2*			
	+P	*Se*	*+P*	*Se*	*+P*	*Se*	*+P*	*Se*
Simulated, -3 dB	*99.98*	*93.70*	*99.98*	*92.91*	*98.71*	*98.61*	*93.67*	*92.80*
Simulated, -6 dB	*99.98*	*91.99*	*99.98*	*86.41*	*97.47*	*97.06*	*89.74*	*88.15*
Simulated, -9 dB	*99.98*	*90.39*	*99.97*	*74.76*	*96.13*	*95.08*	*79.79*	*75.98*
Simulated, -12 dB	*99.98*	*88.67*	*99.96*	*56.65*	*94.56*	*92.95*	*73.54*	*68.69*
Real Data	*83.59*	*76.98*	*81.87*	*73.19*	*85.84*	*86.29*	*69.92*	*70.35*

Considering the simulated data, Table 3 outlines the detailed results for a SNR of -6 dB. Although in average there is often a similar behavior, by analyzing the results per record it turns out that both methods behave rather differently.

Table 3. *Fetal QRS detection results per record at fetal-maternal SNR of -6 dB (results in %; the best tradeoff between +P and Se in terms of the maximum arithmetic mean of both quantities is shadowed for each record).*

Record ID	Kalman		ESC		Kalman		ESC	
	QRS detction method 1				QRS detction method 2			
	+P	Se	+P	Se	+P	Se	+P	Se
1	99.97	89.80	99.97	82.65	95.51	99.84	80.22	83.57
2	99.98	92.59	99.97	77.79	97.64	97.76	90.09	88.89
3	99.98	94.26	99.98	95.58	99.84	99.37	92.51	88.35
4	99.98	93.44	99.98	89.97	98.36	97.78	94.94	94.04
5	99.98	91.06	99.97	72.54	97.13	95.22	85.43	80.16
6	99.98	91.14	99.97	74.38	95.60	95.45	72.40	69.22
7	99.97	92.12	99.97	95.83	95.55	97.02	94.86	97.80
8	100.0	92.64	99.98	96.77	97.67	96.42	99.14	98.95
9	95.98	90.87	99.98	92.18	99.92	94.71	98.10	92.37

Figure 4 contains an example of a signal excerpt which distinctly clarifies the differing behavior of both methods: whereas the KF based approach suppresses well the maternal component, it tends to suppress the fetal part in cases of complete overlaps. ESC behaves completely different: the fetal component usually is not suppressed, but residuals of the mECG may hinder a proper QRS detection considerably.

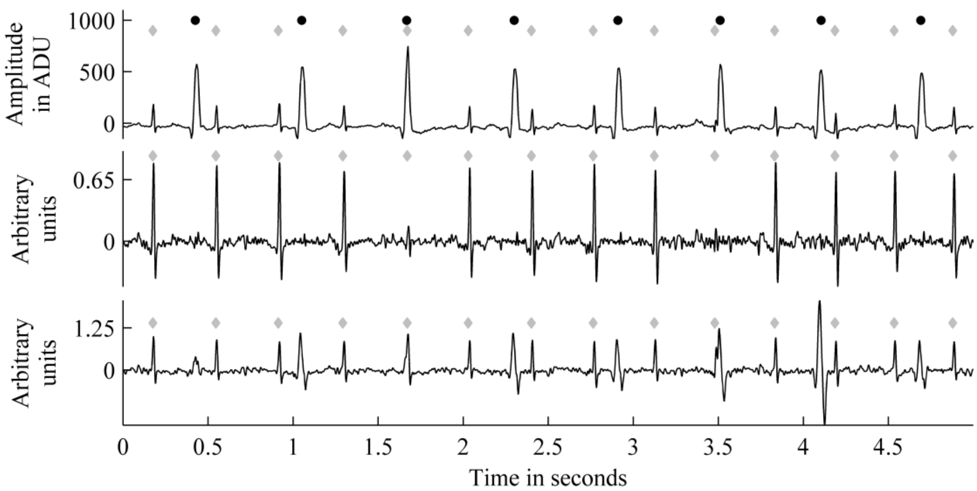

Figure 4. *Simulated abdominal recording (SNR = -9 dB) (topmost signal) with its fetal component as extracted by means of KF (middle signal) and ESC (lowermost signal). Existing maternal (in the topmost signal) and fetal QRS complexes (in all signals) are marked by black circles and gray diamonds, respectively.*

4. Discussion

Although relying on a single abdominal channel, both methods, ESC and the KF based approach, have proven their principle applicability in the context of fetal QRS detection as it was previously stated in the literature. Apparently, in our implementation there is a big drop between the results of simulated and real data. As depicted before, a higher degree of interferences which is contained in the real data is thought to be responsible to a large extend. Some additional degradation may result from the annotation procedure: in the manual annotation more than one abdominal lead was used to identify fetal QRS complexes so that an annotated fetal QRS complex may not necessarily be present in the single lead which is under algorithmic consideration. Moreover, in case of severe interferences even for the expert annotators it is difficult to identify fetal peaks correctly which may further degrade the performance as compared to using simulated data.

Interestingly, as shown in the previous section, the behavior of the extraction methods, and therewith their liability to influence factors, differs considerably. Despite the best mean performance of EKS in combination with QRS detector 2 there is a strong patient specific behavior. In generating an estimation of the mECG, the unbounded Kalman gain can become unstable and estimate an overlapped feto-maternal peak as one higher amplitude maternal complex. On the other hand, the ESC which only adapts the template beats vertically seems inefficient in generating a reliable estimation for maternal signal. Although the beats are allowed to vary up to 20% in amplitude, time variations are not foreseen. In view of this observation, this work may contribute to the development of improved extraction/detection methods by combining the basic ideas of the methods under consideration. Moreover, the real data which was selected for this study suggests that the impact of additional noise sources might be a much more critical factor than the fetal-maternal SNR. Therefore, the incorporation of additional processing steps after removing the maternal ECG is another focus of future works.

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