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Beat-to-beat heart rate detection in multi-lead abdominal fetal ECG recordings

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A R T I C L E I N F O

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Reliable monitoring of fetal condition often requires more information than is provided by cardiotocography, the standard technique for fetal monitoring. Abdominal recording of the fetal electrocardiogram may offer valuable additional information, but unfortunately is troubled by poor signal-to-noise ratios during certain parts of pregnancy. To increase the usability of abdominal fetal ECG recordings, an algorithm was developed that enhances fetal QRS complexes in these recordings and thereby provides a promising method for detecting the beat-to-beat fetal heart rate in recordings with poor signal-to-noise ratios. The method was evaluated on generated recordings with controlled signal-to-noise ratios and on actual recordings that were performed in clinical practice and were annotated by two independent experts. The evaluation on the generated signals demonstrated excellent results (sensitivity of 0.98 for SNR ≥ 1.5). Only for SNR < 2, the inaccuracy of the fetal heart rate detection exceeded 2 ms, which may still suffice for cardiotocography but is unacceptable for analysis of the beat-to-beat fetal heart rate variability. The sensitivity and positive predictive value of the method in actual recordings were reduced to approximately 90% for SNR ≤ 2.4, but were excellent for higher signal-to-noise ratios.

1. Introduction

Reliable monitoring of fetal condition remains one of the largest challenges in obstetrics nowadays. The information provided by cardiotocography, the standard technique for fetal monitoring, is limited and often additional information is required for accurate evaluation of fetal condition. Traditionally, this additional information is obtained from fetal blood sampling [1]. Unfortunately, fetal blood sampling only provides information on fetal condition at a single moment. Further disadvantages of fetal blood sampling are its invasiveness and the difficulty of the procedure. More recently, ST analysis of the fetal scalp electrocardiogram (ECG) has been introduced as addition to cardiotocography [2]. Although ST analysis provides information on a semi-continuous basis, the invasiveness of the method is still a disadvantage, as it can only be applied during labor and is not free of risks [3–5]. Apart from ST analysis, spectral analysis of fetal heart rate variability has also been shown to be a potential predictor for fetal condition [6,7]. Accurate spectral analysis of fetal heart rate variability requires a beat-to-beat measurement of the heart rate and this more or less has restricted the application of spectral analysis to fetal scalp ECG recordings. To overcome this restriction, the availability of a reliable method to record the fetal electrocardiogram non-invasively would be highly appreciated. This would allow for antepartum application of ECG waveform analysis and spectral analysis of fetal heart rate variability.

The fetal electrocardiogram can be measured non-invasively from the maternal abdomen during large parts of pregnancy and the measurement is completely safe for both mother and fetus. Ever since the first measurement of the fetal electrocardiogram by Cremer [8], it has remained a challenge to retrieve the fetal ECG from the mix of physiological signals and noise that is measured on the maternal abdomen. As the main interference is the maternal electrocardiogram, several techniques have been developed to remove the maternal electrocardiogram from the measurements, but with varying success [9–11]. In the 1970s clinical applications of the abdominal fetal electrocardiogram have been introduced, but these have disappeared with the growing success of Doppler ultrasound for antepartum cardiotocography. Recently, abdominal measurement of the fetal electrocardiogram has regained interest [12–14]. Due to the use of multi-lead recordings and advances in signal

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processing techniques, interference of the maternal electrocardiogram is no longer an issue, and the additional information that potentially can be obtained is of high clinical importance [15,16].

Despite all technological improvements, retrieving the fetal electrocardiogram remains a challenge as the amplitude of the measured fetal signal varies during pregnancy and also varies between patients. The various methods that have been developed to separate the fetal electrocardiogram from the measured signals all yield one or multiple channels that contain fetal ECG components. Due to the small amplitude of the fetal electrocardiogram, the signal-to-noise ratio (SNR) of the fetal ECG components in these channels is often relatively poor. Consequently, standard techniques for detecting QRS complexes fail to provide a reliable heart rate for these signals. Averaged heart rates can often be obtained [17], but provide less information and are not suitable for accurate spectral analysis of heart rate variability. Evidently, a need exists for a method that can obtain the beat-to-beat fetal heart rate from fetal ECG recordings with poor signal-to-noise ratio. This need has initiated the development of an algorithm that incorporates a priori knowledge on the fetal electrocardiogram to detect the beat-to-beat heart rate. This work describes this algorithm and evaluates its performance on both generated signals with controlled signal-to-noise ratios and actual measurements that were performed in clinical practice.

2. Algorithm description

The algorithm is intended for detecting the beat-to-beat fetal heart from multi-lead electrophysiological recordings on the abdomen of a pregnant woman. The input of the algorithm consists of multiple channels of abdominal electrophysiological recordings from which the maternal electrocardiogram has been removed. The output that the algorithm provides, contains the recording times at which fetal QRS complexes have been detected.

2.1. Existing QRS detection methods

A wide variety of algorithms for detecting QRS complexes in ECG recordings have been proposed in literature. Most early algorithms have been based on processing of the first derivative of the electrocardiogram or on filtering. Of these algorithms, the Pan–Tompkins method [18] and its numerous variations [19,20] have found widespread use in real-time applications. With increasing computational power, more advanced methods for QRS detection have been introduced, including wavelets [21], neural networks [22], and several other approaches [23]. A review of these methods has demonstrated that the sensitivity and the specificity of the QRS detection are generally very high, but may be significantly affected by the presence of noise and artifacts [23]. To increase the robustness of the QRS detection in the presence of artifacts, multi-lead approaches have been introduced [24,25]. However, direct application of a multi-lead approach to abdominal recordings of the fetal ECG is prohibited by the large amount of noise that may be present in these recordings and the influence that the position of the fetus has on ECG lead orientation.

2.2. Fetal ECG enhancement

The strength of the fetal ECG components in multi-lead abdominal recordings depends among others on the position of the fetus and the electrical conduction towards the maternal abdominal skin, and varies strongly from channel to channel. Calculating linear combinations of these channels, generally improves the signal-to-noise ratio of the fetal ECG. In the fetal vectorcardiogram, of which the various channels are all different projections, the QRS complex is represented by a loop. Due to this loop, phase differences

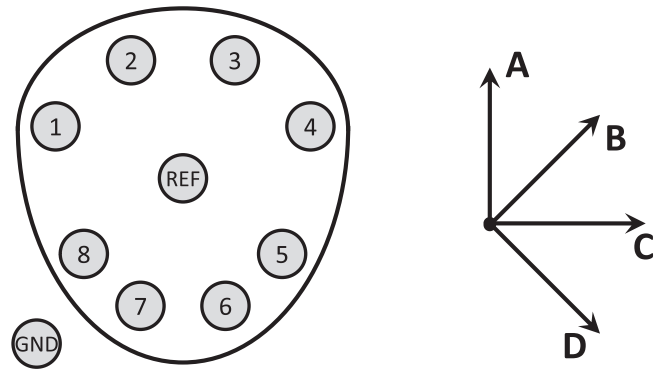

Fig. 1. Used electrode configuration (left) and calculated ECG leads A, B, C, D for linear combinations with equal weights w_i (right).

will exist between the fetal ECG components in different channels. These phase differences will widen the QRS complex when calculating linear combinations of different channels and therefore limit the improvement of the signal-to-noise ratio. In our approach, we correct for this phase difference before calculating the linear combinations. Linear combination of phase difference corrected signals will not only reduce noise, but will also enhance the QRS complex, when compared to standard linear combination. The transformation of the multi-lead input signals $S_i(t)$ into new, non-physiological leads $V_j(t)$ is given by:

$$V_j(t) = \sum_i W_{j,i} \cdot S_i(t - \tau_i). \qquad (1)$$

Here, W is the j by i matrix with the weights for calculating the specific linear combinations and τ_i is the inter-channel phase difference calculated by cross-correlating a selected input signal $S_k(t)$ with each of the other input signals:

$$\tau_i = arg \max_t \left| \sum_{t\prime} S_k^*(t\prime) S_i(t + t\prime) \right| . \qquad (2)$$

Here, $S_k(t)$ is the channel that has the highest correlation with the average of all input channels.

In abdominal recordings, the orientation of the main electrical axis of the fetal heart is a priori unknown. To increase the chances that the calculated non-physiological leads contain significant fetal ECG components, we chose to calculate a set of four linear combinations that, for equal weights, correspond with 0°, 45°, 90° and 135°. This reduced set of four enhanced ECG leads is further processed to detect the beat-to-beat fetal heart rate. Fig. 1 shows the calculated ECG leads (right) and the electrode configuration that was used for our measurements (left).

The matrix W that transforms the multi-lead input signals measured with this electrode configuration into the ECG leads A, B, C and D is defined as:

$$W = \frac{1}{\sum w_i} \begin{pmatrix} w_1 & w_2 & w_3 & w_4 & -w_5 & -w_6 & -w_7 & -w_8 \\ 0 & 0 & \frac{2w_3}{a} & \frac{2w_4}{a} & 0 & 0 & \frac{-2w_7}{a} & \frac{-2w_8}{a} \\ -w_1 & -w_2 & w_3 & w_4 & w_5 & w_6 & -w_7 & -w_8 \\ \frac{-2w_1}{b} & \frac{-2w_2}{b} & 0 & 0 & \frac{2w_5}{b} & \frac{2w_6}{b} & 0 & 0 \end{pmatrix}, \qquad (3)$$

with $a = (\sum_{i=3,4,7,8} w_i / \sum w_i)$ and $b = (\sum_{i=1,2,5,6} w_i / \sum w_i)$ and w_i the maximum value of the absolute cross-correlation that was calculated to determine the inter channel phase difference:

$$w_i = \max \left| \sum_{t\prime} S_k^*(t\prime) S_i(t + t\prime) \right| . \qquad (4)$$

By enhancing the fetal ECG components in the recording, the signal-to-noise ratio of the resulting four leads significantly improves.