A Wavelet-Based Method for Assessing Fetal Cardiac Rhythms from Abdominal ECGs

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Abstract

Fetal heart rate monitoring is widespread all over the world. However, despite recent advances in analysis methods, there are still inherent technical limitations. One of the main challenges is to extract accurate and useful information from the external fetal ECG, which may provide a better non-invasive characterization of the fetal cardiovascular system during the third trimester of pregnancy. In this work, maternal ECG waves were first located using a wavelet transform based system previously developed and validated. Then, a similar strategy with adapted parameters for fetal physiology was applied to detect fetal QRS, excluding signal singularities associated to maternal heartbeats. Single lead based annotations were combined in a single annotator from which RR and HRV fetal measures could be taken. Data provided from PhysioNet 2013 Challenge was considered. The average scores were: 521.43 / 401,50 for event 4 and 32.99 / 29,70 for event 5 on set B /A respectively. The median rate of true positives, false positives and false negatives, normalized by number of fetal beats, found in the (training) set A was, respectively 78%, 17% and 22%. Median FHR estimation error was 2.0 bpm. Correlation between reference and estimated median FHR was 0.65 for estimated FHR>120bpm. The proposed approach seems promising for assessing fetal cardiac rhythms from abdominal ECGs.

1. Introduction

Electronic fetal heart rate (FHR) analysis, introduced into clinical practice about 40 years ago, has provided extensive knowledge on intra-uterine oxygenation and is now the most widely used fetal monitoring technique in industrialized countries [1]. Fetal monitors are widespread in modern obstetric units, and used for the surveillance of selected pregnancies from 24-26 weeks of gestation to term, as recommended by the most prominent scientific associations [1–4]. However, despite recent advances in FHR analysis methods, there are still inherent technical limitations. One of the main challenges in this field is to extract accurate and useful information from the external fetal ECG, which may provide a better non-invasive characterization of the fetal cardiovascular system during the third trimester of pregnancy.

The wavelet transform (WT) provides a description of the signal in the time-scale domain, allowing the representation of its temporal features at different resolutions (scales) according to their frequency content. Thus, regarding the purpose of locating different waves with typical frequency characteristics, the WT is a suitable tool for ECG automatic delineation. An automatic delineation WT based system for ECG recordings was proposed and validated over standard data in [5], with good results.

The objective of this work is to adapt and test the algorithm described in [5], proposing a new wavelet-based methodology for assessing fetal cardiac rhythms from abdominal ECGs, under the scope of the PhysioNet 2013 Challenge.

2. Data and methods

2.1. Data and preprocessing

Data from the Noninvasive Fetal ECG: the PhysioNet / Computing in Cardiology Challenge 2013 (Cin_CCh2013) consists in two sets of one-minute noninvasive abdominal

ECG signals, sampled at 1000 Hz. Learning set used for validation (set A), holds 75 files with reference marks for fetal QRS complex locations, mainly obtained using direct FECG signal, acquired from a fetal scalp electrode (not available). File 54 was excluded from evaluation, following the indications of the Cin_CCh2013 organizers. Open test set used for Cin_CCh2013 scoring (set B), contains 100 recordings but no public reference marks. ECG samples corresponding to no valid observations (special value -32768) were ignored and a notch filter at 0Hz was applied to eliminate baseline fluctuations.

2.2. Wavelet based detection method

Regarding maternal QRS location was applied a single-lead (SL) based delineation system described in detail in [5] and summarized bellow. The prototype wavelet used (a derivative of a smoothing function) allows to obtain a WT at scale 2^m, $w_{x,m}[n]$, proportional to the derivative of the filtered version of the signal $x[n]$ with a smoothing impulse response at scale 2^m. Thus, ECG wave peaks correspond to zero crossings in the WT and ECG maximum slopes correspond to WT's maxima and minima (maximum modulus lines - MML), as can be seen in Fig. 1 in which a fetal ECG and the respective WT signals are plotted. The detection of the fiducial points is carried out across the adequate WT scales and attending to the dominant frequency components. QRS waves are located across scales 2^1 to 2^4, by searching candidates to MML as local maxima above a root mean square (RMS) based scale dependent threshold (Figure 1(b)). Isolated and redundant candidates are eliminated and only the ones that appear as MML pairs of opposite polarity, are considered. QRS location is taken as the zero crossing in between. A 275 msec refractory period is included and search back performed if a too long RR interval is found. QRS onset and end are located using slope based criteria over the WT at scale 2^2. Global marks for main peak location are taken as the median over SL based locations for QRS candidates found in at least two out of the four leads, while boundaries are taken as onset[end] the first[last] SL mark with at least one neighbor mark in other lead.

Fetal QRS complexes location is performed in a similar way, but adapting for fetal physiology, using scales 2^1 to 2^3 only, a 75% lower threshold and without considering the maternal QRS intervals in the RMS computation. MML lines previously associated to maternal QRS are excluded and the time interval for no redundancy between MML of the same polarity was also reduced. A QRS is accepted if it is detected in at least 3 out of the 4 leads, within a 100ms neighborhood. Motivation for these changes is discussed in section 3. Single lead based annotations were combined in a unique annotator from which RR and HRV fetal measures could be taken.

2.3. Performance evaluation

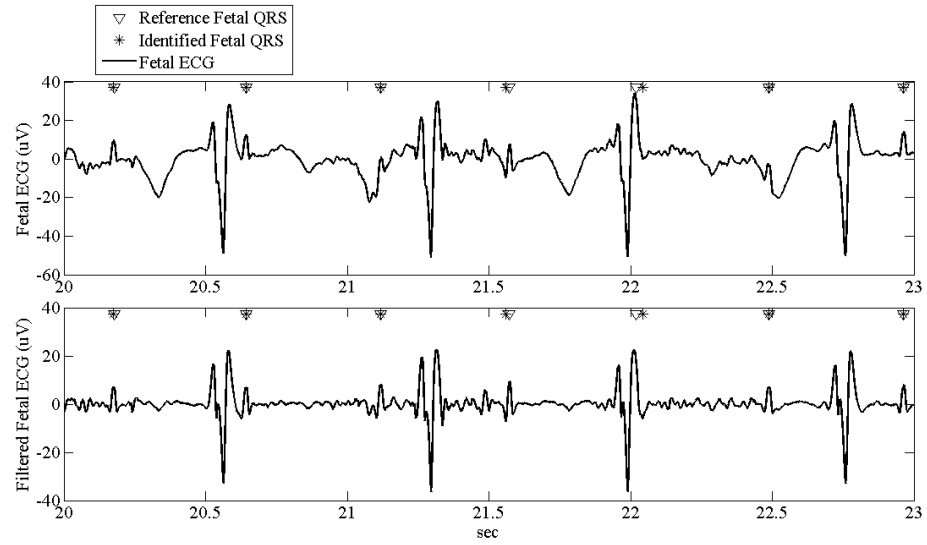
The validation over dataset B was computed by Cin_CCh2013, in the form of two scores that report fetal heart rate measurement (event 4) and fetal RR interval measurement (event 5), according to the challenge description [6]. With respect to the training dataset A, QRS marks differing less than 100 ms from reference marks were considered to be true positives (TP). Detection errors were computed for each record as the rate of true positives (TPn), false positives (FPn) and false negatives (FNn), normalized by the number of reference fetal beats, along with the sensitivity ($Se = TP/(TP + FN)$) and positive predictivity ($P+ = TP/(TP + FP)$). Scores equivalent to events 4 and 5 were computed using software provided by the Cin_CCh2013. Additionally, the median FHR was computed for each record for both original and detected marks, and their difference and correlation were computed.

3. Results and discussion

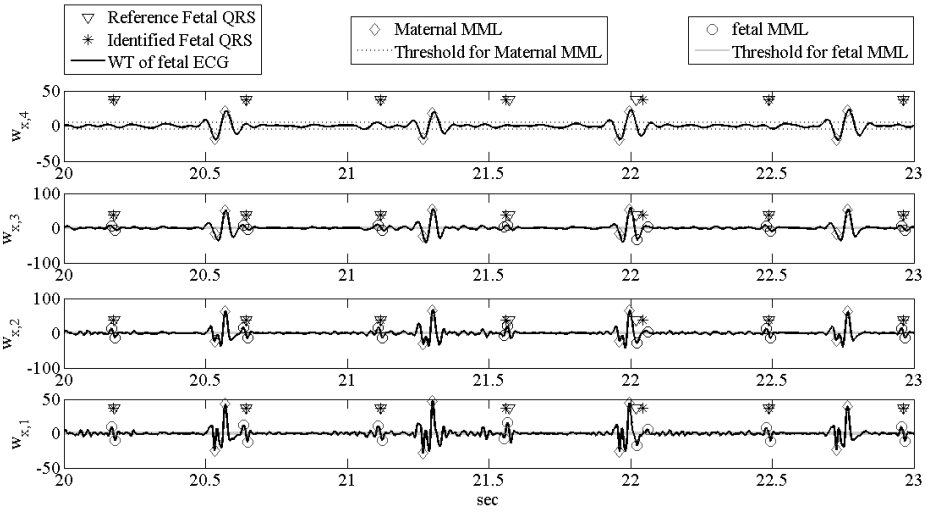
The average scores on set B from entry 1 were: 521.432 for event 4 and 32.987 for event 5. The average of normalized rate errors TPn, FPn and FNn found in the (training) set A was, respectively 71%, 19% and 29%; the average of sensitivity and positive predictivity found were 71% and 77%, respectively. The average scores of the Challenge computed on set A were respectively 401,50 and 29,70 for events 4 and 5. The results over set A files are summarized in Fig. 2 for both errors, Se, $P+$ and scores. Considering the median, a central measure known to be more robust to outliers than average, were found the following values for normalized rate errors TPn, FPn and FNn, sensitivity and positive predictivity and scores 4 and 5, respectively: 78%, 17% and 22%, 78% and 82%, 199.06 and 27, respectively. Median FHR estimation error was 2.0 bpm. Correlation between reference and estimated median FHR was 0.33, which increased to 0.65 when considering only records for which for the estimated FHR>120bpm (Fig. 3).

The original detection algorithm [5] was expected to be able to locate maternal QRS. No systematic validation of that fact could be done due to the lack of reference annotations for maternal QRS locations. Nevertheless according to the visual inspection it performs correctly, as illustrated in Figure 1(b) where maternal QRS complexes are clearly visible and associated MML lines are marked as diamonds.

For fetal heart beats detecting, adaptations are clearly required. First of all the WT scale 2^4 is not useful, as fetal QRS MML are not relevant in $w_{x,4}[n]$ signal, as illustrated in Figure 1(b). This is explained by the known fact that while adult QRS complex content can range from almost zero to 40 Hz, the frequency content of fetal QRS is bellow 20 Hz [7]. Also the lower power of fetal contribution, even excluding from the threshold computation maternal QRS



(a)Fetal ECG



(b)WT of Fetal ECG

Figure 1. Illustration of the fetal QRS detection over fetal ECG and WT signals:(a) original and filtered (notch) fetal ECG,reference and identified fetal QRS complexes; (b) WT signals of the fetal ECG, reference and identified fetal QRS complexes, and MML (maternal and fetal).

intervals, requires a lower threshold for fetal MML detection. The price of a 75% reduction is a higher number of candidates to MML. That did not represent a problem as the same protections against isolated and redundant local maxima are sufficient to eliminate the non relevant ones in most of the cases. The change of the time interval for redundancy is an adaptation to the shorter duration of fetal QRS complexes: MML associated to secondary QRS waves (like Q and small S waves) should appear closer.

The gestational age and type of presentation (breech or cephalic) are important factors that may have been related with the records associated with lower quality. For instance, the influence of the vernix caseosa between 28 and 32 weeks of gestation leads to a lower amplitude of the fetal ECG. As these factors were unknown to the Cin_CCh2013 participants, it was not possible to confirm whether they may have been associated with records presenting higher scores. Therefore, this is an important aspect to be evaluated in the future.

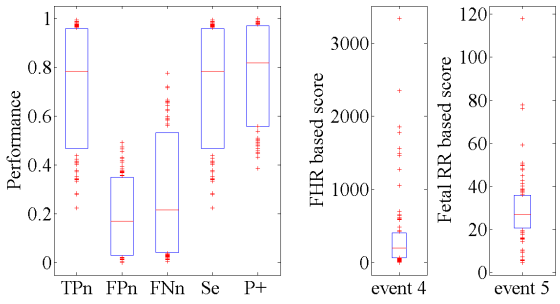


Figure 2. Box-plot diagrams for the distribution of errors, Se, $P+$ and scores and scores over files in dataset A (central box goes from 1^{st} to 3^{rd} quartiles, with horizontal line marking the median).

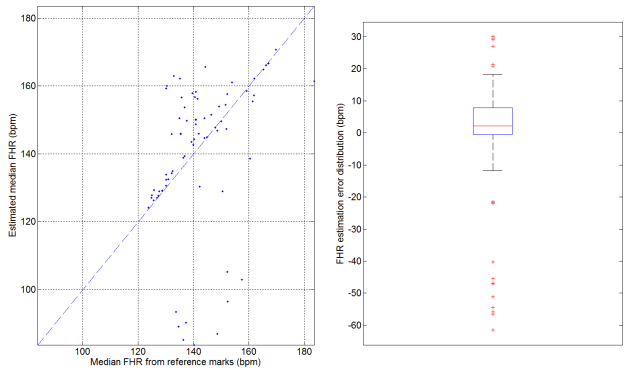


Figure 3. Estimated median FHR versus median FHR obtained from reference marks (on the left) and distribution of the median FHR estimation error (on the right).

4. Concluding remarks

The proposed approach seems promising for assessing fetal cardiac rhythms from abdominal ECGs. Nevertheless, a high number of errors were present for some files. The performance of the detector strongly depends on the quality of the data, and thus pre-processing methods for discarding very low quality signals should be considered. This research was focused in the correct location of the fetal QRS locations. No post processing attending to cardiac rhythm was considered in the errors rate or scores computation. This should be taken into account when estimating FHR and thus further evaluation on this is required. The proposed methodology does not require a specific transformation/separation method regarding the fetal ECG analysis, being used the same as for maternal ECG processing.

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