Fetal movement detection based on QRS amplitude variations in abdominal ECG recordings

M.J. Rooijakkers, H. de Lau, C. Rabotti, S.G. Oei, J.W.M. Bergmans, and M. Mischi

Abstract— **Evaluation of fetal motility can give insight in fetal health, as a strong decrease can be seen as a precursor to fetal death. Typically, the assessment of fetal health by fetal movement detection relies on the maternal perception of fetal activity. The percentage of detected movements is strongly subject dependent and with undivided attention of the mother varies between 37% to 88%. Various methods to assist in fetal movement detection exist based on a wide spectrum of measurement techniques. However, these are typically unsuitable for ambulatory or long-term observation. In this paper, a novel method for fetal motion detection is presented based on amplitude and shape changes in the abdominally recorded fetal ECG. The proposed method has a sensitivity and specificity of 0.67 and 0.90, respectively, outperforming alternative fetal ECG-based methods from the literature.**

I. Introduction

Registration and evaluation of fetal movements give a valuable indicator of fetal health, as a decrease in fetal motility can be seen as a precursor to fetal death, sometimes by as much as several days [1]. Typically employed methods to assess fetal health from fetal movements are based on a non-stress test, which counts the number of fetal movements within a set amount of time. The literature describes various methods to determine fetal risk, which range from counting a minimum of 10 movements in 12 hours to counting the number of movements in a single hour [2], [3], [4].

Currently, the methods that are most often employed to count fetal movements consist of the mother counting fetal activity based on her perception [3], [4], [5]. However, it has been shown that only 37% to 88% of fetal movements are felt in case the mother is lying still and paying active attention. In other settings, the actual frequency of fetal movements as well as the ability of the mother to perceive these movements are affected by many factors like maternal activity, position, stress, and attention level [5]. Detection of fetal movements is, therefore, strongly subject dependent. To achieve reliable results, active attention needs to be paid when counting during a period sufficiently long to account for the fetal rest-activity cycles [1], [5]. Counting to 10 fetal movements within a 2 hour time slot is a suitable target, while it is short enough to yield high compliance and acceptance rates [6].

Various systems for automatically detection of or assistance in fetal movement detection exist. These can be categorized based on abdominal movements [7], [8], [9], electrical impedance measurements [10], electromagnetic recordings [2], ultrasound imaging [11], [12], [13], Doppler ultrasound [14], [15], [16], fetal phonogram [17], optical flow displacement histograms [18], as well as abdominal ECG based methods, which include temporal and spatial ECG shape identification [19] and fetal VCG loop alignment [20]. The most reliable detection method is continuous ultrasound imaging with manual identification by a medical expert, which is very labor intensive and not suitable for long-term observation. Only the methods based on the abdominal ECG are suitable for long-term ambulatory use and, therefore, the method proposed by Vullings *et al.* is used as a reference [20].

Continuous monitoring of fetal movements in an ambulatory setting can greatly increase the sensitivity of fetal movement counting in predicting fetal situations resulting in fetal asphyxia or preterm birth. Additionally, due to the use of long term measurements, the fetal rest-active cycle can be taken into account. To allow for continuous long-term ambulatory counting of fetal movements, the measurement method should be robust to movement artifacts and low-power; therefore the signal processing to determine periods of movement should be simple to reduce processing power. The method presented by Vullings *et al.* allows for ambulatory detection of fetal movement based on abdominal ECG measurements. However, multi-channel measurements and complex signal processing techniques required for fetal VCG loop alignment increase the power requirements.

In this paper a new method for fetal motion detection is presented, which is based on variations of the amplitude in the fetal QRS complex. The method is based on the premise that the fetal ECG waveform as observed on the maternal abdomen changes as a result of a displacement of the cardiac vector with respect to the measurement electrodes [21]. The change in QRS-wave height and shape can, therefore, be used to indicate a thoracic movement and be used to give an indication of the fetal motility.

II. Methodology

The detection of fetal movements in the presented algorithm is based on tracking of changes in amplitude and shape of the fetal QRS complex over time. Therefore, it is essential that the fetal QRS complexes are detected accurately and any complexes distorted by noise or artifacts are removed. To this end, a preprocessing stage is used prior to feature extraction and fetal motion estimation.

This work was supported by the Dutch technology foundation STW

M.J. Rooijakkers, H. de Lau, C. Rabotti, J.W.M. Bergmans, and M. Mischi are with the Faculty of Electrical Engineering, University of Technology Eindhoven, 5612 AZ, Eindhoven, The Netherlands m.j.rooijakkers@tue.nl

S.G. Oei is with the Perinatology and Obstetrics department, Máxima Medical Center, 5504 DB, Veldhoven, The Netherlands

978-1-4244-7929-0/14/$26.00 ©2014 IEEE

A. Preprocessing

The first preprocessing step consists of band-pass filtering the signal between 2 Hz and 98 Hz to remove all out-of-band noise and a notch filter at 50 Hz to remove powerline interference. Next, maternal R-peak detection is performed followed by detection of the fetal R-peaks while blanking all intervals ± 50 ms around the maternal R-peaks. For detection of both the maternal and fetal R-peaks, the algorithm presented in [22] was used.

Some controls are implemented to reduce the number of misdetected peaks and fetal R-peaks which are affected by noise or artifacts. Detected peaks with an amplitude over three times the average peak height (determined over the last 5 seconds) and peaks within ± 100 ms from a maternal R-peak are excluded. Additionally, the exact location of the R-peak was adjusted to align with the apex of the QRS-complex by selecting the maximum in a 5 ms interval around the detected peak location. In case the sign of the detected peak switched with respect to the mean orientation of the previous 20 QRS peaks, the search range was extended to ± 25 ms to account for a misdetection of a Q- or S-peak.

As the amplitude of the fetal QRS is very low and prone to interference by artifacts and noise, a clean QRS-complex is created. To this end, all accepted fetal QRS-complexes within an interval of 5 seconds are averaged resulting in the clean fetal QRS (QRS_f) with a length of 50 ms, as shown in Fig. 1a. Depending on the actual fHR and the number of accepted QRS-complexes, the number of complexes used for estimation of an average QRS-complex can be anywhere between 0 and 20.

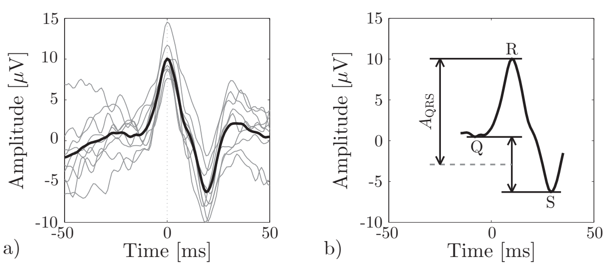

Fig. 1. Example of a clean fetal QRS-complex. a) Multiple aligned fetal QRS-complexes (thin gray) and the mean (thick black). b) Extraction of the QRS amplitude A_{QRS} from the clean fetal QRS-complex QRS_f.

B. Feature extraction

Two features are extracted from the cleaned QRS complex QRS_f, the amplitude and the correlation coefficient r. The amplitude is related to scaling due to translational movements of the fetus. The correlation coefficient, on the other hand, gives a similarity in signal morphology due to rotations with respect to the abdominal electrodes without considering the signal amplitude. These two features can therefore be considered independent.

The amplitude of each averaged fetal QRS-complex is defined as the difference between the value at the R-peak position and the mean of the Q- and S-peaks, as shown in Fig. 1b. Here the Q- and S-peaks are defined by the minimum in a 25 ms interval before and after the R-peak, respectively. In the resulting amplitude signal, A_{QRS}, periods of fetal motion can be recognized as segments with shifts in amplitude due to a change in position or an oscillatory signal due to repeated fetal motion. To remove noise induced artifacts and emphasize the amplitude shifts due to fetal motion, A_{QRS} is band-pass filtered by convolving with the first derivative of a Gaussian wave defined as

$$\varphi_i = \frac{i}{\sqrt{s}} e^{-\frac{i^2}{2\cdot s}}, \tag{1}$$

where s is a time scaling factor set to 6 and i is the sample index, which is limited to the range $\Delta i = [-10,\ 10]$. Finally, the translational motion feature M_T is determined by calculating the root mean squared value over a period of 10 seconds and is defined for each QRS complex as

$$M_T = \sqrt{\frac{1}{T} \sum_{t=-T/2}^{T/2} (A_{\mathrm{QRS}} * \varphi)_t^2}, \tag{2}$$

where $*$ is the convolution operator and $T = 10$ s.

The amount of fetal rotation is estimated using the correlation coefficient r. The feature for rotational motion M_R is obtained by subtracting r from 1, which for each QRS-complex is given by

$$M_R = 1 - \frac{\sum_{i=1}^{N} (x_i - \overline{x})(y_i - \overline{y})}{\sqrt{\sum_{i=1}^{N} (x_i - \overline{x})^2 \sum_{i=1}^{N} (y_i - \overline{y})^2}}, \tag{3}$$

where x and y are the averaged QRS-complexes QRS_f spaced by 10 s, i is the sample index, and N is the number of samples in each QRS-complex. Here, M_R is in the range $0 \leq r \leq 2$, the value of which increases with increasing rotation-induced differences between consecutive QRS complexes.

C. Fetal movement detection

In the two-dimensional space spanned by M_R and M_T an elliptical threshold is used to classify between fetal movement and fetal rest. The elliptical threshold is a trade-off between two independent thresholds and a single linear one and is defined as

$$M_T = \sqrt{R^2 - (\epsilon \cdot M_R)^2}, \tag{4}$$

where R is the radius of the ellipse in the direction of M_T and ϵ is a measure of eccentricity. All points outside the ellipse defined above are considered motion, while all points inside are considered fetal rest. The parameters R and ϵ in (4) are optimized by minimizing the cost function $C = 1/\left(\sqrt{\mathrm{sensitivity}} + \mathrm{specificity}\right)$ for each patient, based on the obtained sensitivity and specificity as defined in Section III. The cost function favors the specificity because it is a more relevant clinical parameter since prolonged periods with a lack of fetal movement are an important indicator of possible fetal distress. A 40-s wide median filter is applied to the detection output to reduce short artifact-induced detections of motion and narrow gaps between motion intervals.

III. Validation

A. Dataset

The dataset is based on 4 abdominal ECG recordings of 30 minutes each on women at gestational ages ranging from 22 to 27 weeks. The recordings were made at the Máxima Medical Center, Veldhoven, The Netherlands, at a sampling rate of 1 kHz using a NEMO system (Maastricht Instruments BV, the Netherlands). Eight electrodes were placed on the maternal abdomen in a circle around the umbilicus as presented in [23]. Only lead 8, at the bottom right of the belly, was used for validation of the presented algorithm. Simultaneous ultrasound recordings were performed using an Aloka SSD1100 ultrasound device (Aloka, Japan). The classification between episodes with and without fetal movement from the ultrasound recordings was obtained by visual inspection by a medical expert. In total, four classes of events were defined: major fetal movement, minor fetal movement, no fetal movement, and probe movement. Here, periods with almost continuous motion of multiple limbs or the thorax are considered major movements, while intermittent movements with one of the limbs is considered a minor movement. Periods containing probe movements (5:28 minutes) were excluded from the validation.

B. Quality measures

The quality of movement classification is expressed by its sensitivity and specificity, which is determined for all fetal ECG recordings by comparing the detected state of fetal motility with the reference annotations. The sensitivity and specificity are defined as $TP/(TP+FN)$ and $TN/(TN+FP)$, respectively, with TP = true positives, FN = false negatives, TN = true negatives, and FP = false positives. Major fetal movement in this case is considered as positive, while the absence of movement and minor movement are considered a negative. The sensitivity therefore gives an indication of the algorithm's ability to correctly detect periods of fetal movement, while the specificity indicates the reliability with which fetal rest is determined.

IV. Results

Fig. 2 shows an example of the QRS amplitude A_{QRS} and correlation coefficient r for an abdominal ECG recording.

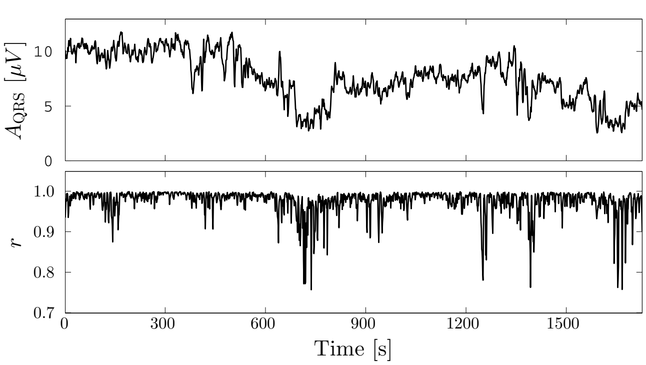

Fig. 2. Estimates of the QRS amplitude A_{QRS} (top) and correlation coefficient r (bottom) over time for recording 4.

In Fig. 3 the fetal movement parameters M_R and M_T of the same recording are depicted together with the movement annotations based on ultrasound recordings as well as the detected periods of movement using the presented method. Annotations of minor fetal movements are shown in the figure, but are considered equal to periods without fetal movement.

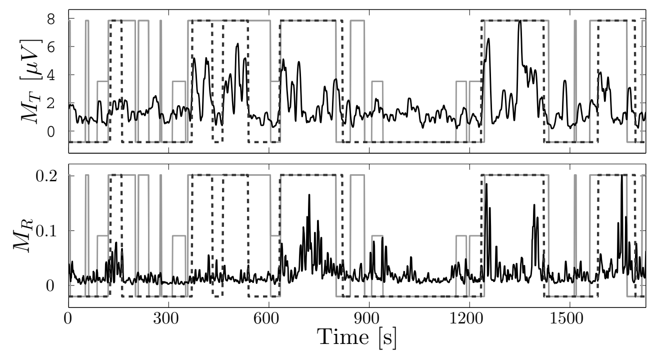

Fig. 3. The top and bottom plot show the fetal movement features M_T and M_R, respectively, for abdominal ECG recording 4. A high and average reference signal (solid gray) indicates periods of major and minor fetal movement, respectively, while a low reference indicates fetal rest, as determined from ultrasound measurements. The dotted line indicates detections of fetal movement by the presented method based on a combination of the parameters M_T and M_R.

Fig. 4 shows the fetal movement parameters M_R and M_T as two orthogonal axes during periods of fetal movement and periods without movement. Black squares indicate QRS complexes during periods without annotated fetal movement, while the gray circles indicate QRS complexes during periods of major fetal movement.

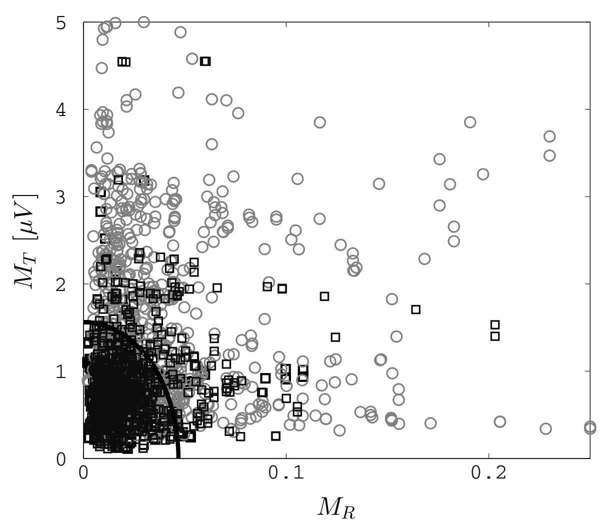

Fig. 4. Fetal movement parameters M_T plotted as a function of M_R for one of the fetal ECG recordings, both for periods with major fetal movement (grey ◯) and with minor or no fetal movement (black □). The solid black line indicates the elliptical threshold used for automatic classification of movement/no-movement periods.

Table I shows the sensitivity and specificity of the proposed method for fetal motion detection for each of the recordings in the used dataset.

TABLE I
SENSITIVITY AND SPECIFICITY OF ALL MEASUREMENTS

Recording	Sensitivity	Specificity
# 1	1.00	0.99
# 2	0.43	0.80
# 3	0.57	0.89
# 4	0.69	0.93
Total	0.67 ± 0.24	0.90 ± 0.08

V. DISCUSSION

A new method for detection of fetal motion is presented, which can be used to give an indication of the fetal motility from abdominal ECG recordings. The method is based on tracking changes in position and orientation of the fetal cardiac vector by observing the variations in QRS-wave height and shape. It allows for reliable registration of fetal motion from a single bipolar abdominal ECG lead and, hence, is suitable for observation of fetal motility in an ambulatory setting.

When applying the proposed algorithm to the introduced dataset, an overall sensitivity of 0.67 and specificity of 0.90 is obtained. The results compare favorably to the method proposed by Vullings *et al.* , which obtains a sensitivity and specificity of 0.47 and 0.87, respectively, using a multi-lead abdominal ECG measurement and vector cardiographic loop alignment [20]. The relatively low sensitivity compared to the specificity can be explained by the fact that both movements of the limbs and movements of the thorax are considered clinically relevant, and have been annotated, while only the latter can be expected to impact M_T or M_R.

The sensitivity of the proposed method, which entails the reliability with which periods of movement are detected, is comparable to that of manual counting based on maternal perception. Manual counting achieves a sensitivity of 0.37 to 0.88 in case the mother-to-be is lying still and paying active attention. When counting over a prolonged period of time or when counting while performing additional tasks, this sensitivity will drop further [1], [5], [6]. For clinicians, the reliability with which the absence of fetal movement is determined, i.e. the specificity, is of a higher importance. This is because prolonged periods with a lack of fetal movement are an important trigger indicating possible fetal distress.

In conclusion, the results of the proposed method for fetal motion detection surpass those of alternative ECG-based methods from the literature and are comparable to detection based on maternal perception. Because the method operates on only a single bipolar abdominal channel it is well suited for long-term ambulatory registration of fetal motility.

REFERENCES

[1] A. D. Bocking, "Assessment of fetal heart rate and fetal movements in detecting oxygen deprivation in-utero," *European Journal of Obstetrics & Gynecology and Reproductive Biology*, vol. 110, Supplement, no. 0, pp. S108 – S112, 2003, the Regulation of Fetal Growth, Fetal Oxygen Supply and Intrauterine Development.

[2] E. Sadovsky, Y. Mahler, W. Polishuk, and A. Malkin, "Correlation between electromagnetic recording and maternal assessment of fetal movement," *The Lancet*, vol. 301, no. 7813, pp. 1141 – 1143, 1973, originally published as Volume 1, Issue 7813.

[3] J. Pearson and J. Weaver, "Fetal activity and fetal wellbeing: an evaluation," *Br Med J*, vol. 1, pp. 1305 – 1307, May 1976.

[4] L. R. Leader, P. Baillie, and D. J. van Schalkwyk, "Fetal movements and fetal outcome: A prospective study," *Obstetrics & Gynecology*, vol. 57, no. 4, pp. 431 – 436, 1981.

[5] J. F. Fren, *et al.*, "Fetal movement assessment," *Seminars in Perinatology*, vol. 32, no. 4, pp. 243 – 246, 2008, antenatal Testing: A Re-Evaluation.

[6] T. R. Moore and K. Piacquadio, "A prospective evaluation of fetal movement screening to reduce the incidence of antepartum fetal death," *American Journal of Obstetrics and Gynecology*, vol. 160, no. 5, Part 1, pp. 1075 – 1080, 1989.

[7] E. Sadovsky, *et al.*, "Fetal movements recorder, use and indications." *Int J Gynaecol Obstet*, vol. 15, no. 1, pp. 20 – 24, 1977.

[8] K. Nishihara, S. Horiuchi, H. Eto, and M. Honda, "A long-term monitoring of fetal movement at home using a newly developed sensor: An introduction of maternal micro-arousals evoked by fetal movement during maternal sleep," *Early Human Development*, vol. 84, no. 9, pp. 595 – 603, 2008.

[9] E. Ryo, K. Nishihara, S. Matsumoto, and H. Kamata, "A new method for long-term home monitoring of fetal movement by pregnant women themselves," *Medical Engineering & Physics*, vol. 34, no. 5, pp. 566 – 572, 2012.

[10] M. Utsu, "Studies on the measurement of fetal breathing movement by the impedance method (author's transl)." *Nihon Sanka Fujinka Gakkai Zasshi*, vol. 33, no. 1, pp. 87 – 96, Jan. 1981.

[11] K. Maeda, "New ultrasonic doppler fetal actograph and continuous recording of fetal movement," *Nihon Sanka Fujinka Gakkai Zasshi*, vol. 36, no. 2, pp. 280 – 288, Feb. 1984.

[12] R. E. Besinger and T. R. B. Johnson, "Doppler recordings of fetal movement: Clinical correlation with real-time ultrasound," *Obstetrics & Gynecology*, vol. 74, no. 2, pp. 277 – 280, 1989.

[13] A. Kribche, F. Tranquart, D. Kouame, and L. Pourcelot, "The actifetus system: A multidoppler sensor system for monitoring fetal movements," *Ultrasound in Medicine & Biology*, vol. 33, no. 3, pp. 430 – 438, 2007.

[14] T. Wheeler, G. Gennser, R. Lindvall, and A. J. Murrills, "Changes in the fetal heart rate associated with fetal breathing and fetal movement," *BJOG: An International Journal of Obstetrics & Gynaecology*, vol. 87, no. 12, pp. 1068 – 1079, 1980.

[15] R. Rabinowitz, E. Persitz, and E. Sadovsky, "The relation between fetal heart rate accelerations and fetal movements," *Obstetrics & Gynecology*, vol. 61, no. 1, pp. 16 – 18, 1983.

[16] J. A. DiPietro, D. M. Hodgson, K. A. Costigan, S. C. Hilton, and T. R. Johnson, "Development of fetal movement fetal heart rate coupling from 20 weeks through term," *Early Human Development*, vol. 44, no. 2, pp. 139 – 151, 1996.

[17] N. Colley, *et al.*, "The fetal phonogram: a measure of fetal activity." *Lancet*, vol. 1, no. 8487, pp. 931 – 935, Apr. 1986.

[18] C. Surlea, F. Kurugollu, P. Milligan, and S. Ong, "Foetal motion classification using optical flow displacement histograms," in *Proceedings of the 4th International Symposium on Applied Sciences in Biomedical and Communication Technologies*, ser. ISABEL '11. New York, NY, USA: ACM, 2011, pp. 156:1 – 156:5.

[19] J. A. Crowe, D. James, B. R. Hayes-Gill, C. W. Barratt, and J.-F. Pieri, "Fetal surveillance," GB Patent WO 2005/039 410 A1, May 6, 2005.

[20] R. Vullings, M. Mischi, S. Oei, and J. Bergmans, "Novel Bayesian vectorcardiographic loop alignment for improved monitoring of ECG and fetal movement," *IEEE Trans. Biomed. Eng.*, vol. 60, no. 6, pp. 1580 – 1588, Jun. 2013.

[21] T. Oostendorp, *Modelling the fetal ECG: een wetenschappelijke proeve op het gebied van de geneeskunde en tandheelkunde*. Katholieke Universiteit te Nijmegen, 1989.

[22] M. J. Rooijakkers, C. Rabotti, S. G. Oei, and M. Mischi, "Low-complexity r-peak detection for ambulatory fetal monitoring," *Physiological Measurement*, vol. 33, no. 7, pp. 1135 – 1150, 2012.

[23] R. Vullings, *et al.*, "Dynamic segmentation and linear prediction for maternal ECG removal in antenatal abdominal recordings," *Phys. Meas.*, vol. 30, no. 3, pp. 291 – 307, Feb. 2009.