fetal movement activity,
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AUTOMATED DETECTION OF FETAL MOVEMENTS IN DOPPLER ULTRASOUND SIGNALS VERSUS MATERNAL PERCEPTION

Analysis of movement activity is important since it enables detection of nonreactive fetal heart rate recordings. The aim of the study was to develop an algorithm for automated detection of the fetal movement activity (actogram), based on analysis of the Doppler ultrasound signal, and to evaluate a reliability of the actogram as a source of information about the fetal movements. Bandpass filtering (20-80 Hz) was used to separate the actogram signal describing the fetal movement activity. Simultaneously there were recorded the markers of fetal movements perceived by mother, being the reference information. For the determination of the binary actogram, the authors proposed an algorithm in which the classification threshold was estimated at the beginning of each recording and was adaptively modified during its duration. The algorithm ensured detection of up to 89% of movement episodes corresponding to movements perceived by mother. At the same time almost as high number of episodes not related to the reference information was recognized. Obtained results revealed that the automated analysis of fetal movements is characterized by much higher sensitivity of movement episode detection compared to the maternal perception.

1. INTRODUCTION

Cardiotocography (CTG) is the primary noninvasive biophysical method for assessment of a fetal state. It is based on the fact that correct activity of fetal heart reflects good intra-uterine oxygenation. Cardiotocographic monitoring relies on simultaneously recording of the fetal heart rate (FHR), uterine contractions and fetal movement activity [4]. The analysis of the fetal movement activity is important since it enables detection of the nonreactive recording, i.e. when accelerations patterns in the FHR signal are not associated with the fetal movement episodes [5].

At first, the information on fetal movement activity was obtained from fetal movements perceived by mother. This technique is rather subjective and depends on many factors including: gestational age, the amount of amniotic fluid or the fetal size [6], [9]. The most reliable method, allowing for determination of the type and volume of the movement is an ultrasound imaging. Unfortunately, availability of this medical procedure is limited, due to a high cost of equipment and medical staff involvement for a quite long time.

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Thus, the signal called actogram has become an integral part of the cardiotocographic trace providing information on the fetal movement activity [12]. The actogram, just like the fetal heart rate signal, is obtained through the Doppler ultrasound method, basing on the fact that instantaneous speed of the fetal movements is lower than for valves or walls of the fetal heart [1], [2], [8], [14]. Depending on the fetal movement type the speed varies from 1 to 3 cm/s, that corresponds to a frequency range from 20 to 80 Hz for the ultrasound transducer operating at 2 MHz [11], [13], [16]. Whereas, the components originating from the fetal heart activity are between 150 and 250 Hz for walls, and from 250 to 600 for valves [3], [7], [15]. Classical bandpass filtering is used to separate the signal bandwidth describing the fetal movement activity.

There are two forms of the fetal actogram representation. The continuous actogram is formed by the values normalized in the range from 0 to 100 units, and plotted on a paper as spike-like waveform (Fig.1). An alternative form is a binary actogram which shows the occurrences of fetal movement activity episodes without any information on the movement intensity. The binary actogram is represented only by two values: one fetal movement recognized, and zero not recognized. The binary signal could be obtained from the continuous one most simply by using an empirically selected threshold level, and then movement activity is plotted in a form of graphical markers.

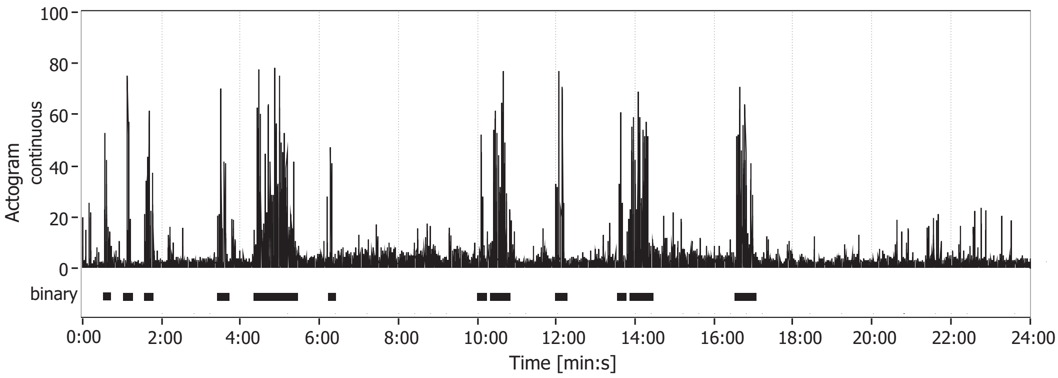

Fig. 1. The continuous and binary representations of the fetal actogram, the signal describing the fetal movement activity was obtained via the Doppler ultrasound channel.

The aim of the study was to develop an algorithm for automated detection of the fetal movement activity based on analysis of the Doppler ultrasound signal, and to evaluate a reliability of the fetal actogram as the source of information about the fetal movement activity. Our efforts were focused on the method for transforming the continuous actogram into the binary one. Since the proposed algorithm was designed to be implemented in a bedside fetal monitor, the essential requirement was its limited computational complexity.

2. METHODOLOGY

The research database contains signals from routine procedures of cardiotocographic monitoring of pregnant women carried out in Clinical Hospital of Silesian Medical University in Katowice. The Doppler signals of frequency band from 20 to 300 Hz were recorded simultaneously with the FHR signal quality information and the markers of fetal movements perceived by the mother being the reference information. As long as the mother keeps the manual marker being pressed, the movement activity status is set to on in the fetal monitor. The Doppler signals were sampled at frequency of 1386 Hz and were stored together with the fetal movement markers from a serial RS232 output, being a standard in the fetal monitor used.

The final research material comprised 11 recordings (each twenty minutes long) from patients in various gestational age - between 26 and 41 week of pregnancy.

When analyzing the durations of movements perceived by the mother we noted that short movements not exceeding two seconds were dominating. Partly, it was caused by the fact that despite instructing the mother to keep the movement marking button pressed as long as she perceives the fetal movement, she often intuitively just ”clicks” the button. Consequently, the movements of a longer duration were usually represented by several short markings. Therefore, the markers occurring closer than empirically established period of 5 s, were merged together to better represent a real fetal movement activity. Additionally, the fetal movements occurring during the FHR signal loss episodes were excluded from further analysis. Finally, the 142 fetal movement episodes perceived by mother with total duration of 729 seconds were established as the reference information and they were used to evaluate the performance of the developed algorithm.

The Doppler signal was processed in one-second window to determine the continuous actogram, and the value of binary actogram was set to one when the algorithm classified this segment as the fetal movement activity. Such one-second resolution of binary actogram allowed for the on-line performance of the algorithm build-in a fetal monitor and was enough to be plotted on a thermal paper. In the first stage of analysis the Doppler signal (20-300 Hz) underwent the low-pass filtering using the Butterworth filter (second order with cut-off frequency of 80 Hz) to obtain the frequency band of 20-80 Hz corresponding to the fetal movement activity (Fig.2). Next, in order to limit the computational efforts, the signal was resampled to 231 Hz, and the absolute values of successive samples were normalized into the range of 0-100, that led to generally established representation of the continuous actogram.

The essential step in the process of fetal movement detection on the basis of the Doppler signal, is the analysis of continuous actogram leading to determination of a more popular the binary equivalent. The simplest method is comparing the continuous actogram with a fixed threshold level. Such procedure has been used in various fetal monitors with automated evaluation of the fetal movement activity (e.g. TOITU MT-430 Japan) [11]. Anywhere the actogram exceeds the established threshold level the fetal movement is detected. Unfortunately, this method is not optimal, because both the amplitude of the continuous actogram in fragments corresponding to movement activity, as well as the amplitude of the background noise changes significantly between particular recordings. Nevertheless, this simplest method was also applied to our database to compare the results with our new proposed algorithm.

An analysis of continuous actogram in segments corresponding to the FHR signal loss may be unreliable. Thus, if patterns allowing correct measurement of the FHR are not observed in the Doppler signal, that may suggest that the emitted ultrasonic beam does not cover the fetal body. The change in the relative position between the fetus and the ultrasound transducer may be caused by movements of the mother. Analysing the collected recordings we found signals where during the FHR signal loss (Fig.3A) a significant increase of intensity of the continuous actogram was observed (B), as well as the signals without any significant changes (C and D). Therefore, both for the fetal movements perceived by mother and detected using the algorithm proposed, the movements corresponding to the FHR loss segments were excluded from the analysis, and hence the values of binary actogram were set to zero, which means no movement.

In all validated fragments of the continuous actogram (i.e. without the FHR signal loss) the analysis consisted in classifying of a given fragment as the fetal movement activity episode or not. In the proposed algorithm the threshold level was estimated at the beginning of each monitoring session and then was adaptively modified with its progress in time. With every successive one-second segment of the continuous actogram the maximum amplitude was calculated, and then stored into a shift register (Fig.2). In the initial stage, when the actogram amplitude level

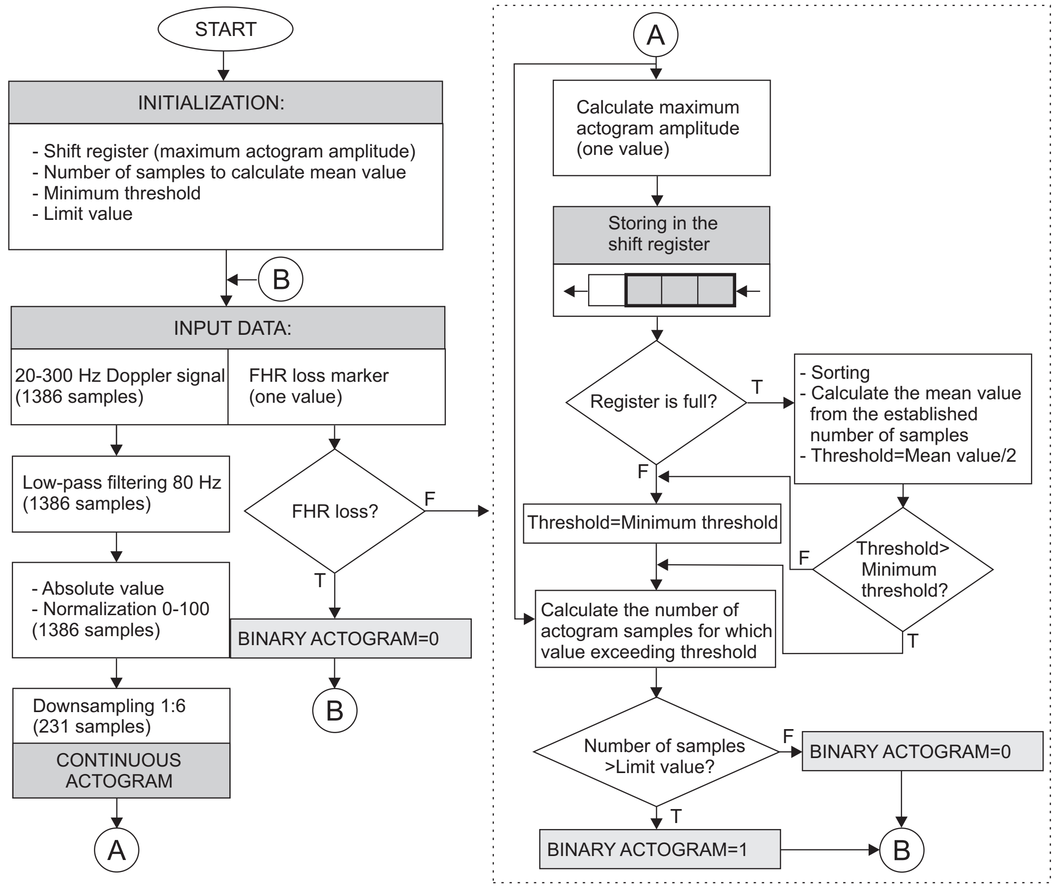

Fig. 2. A general diagram presenting the algorithm for the determination of continuous and binary actograms basing on analysis of one-second window in the Doppler signal.

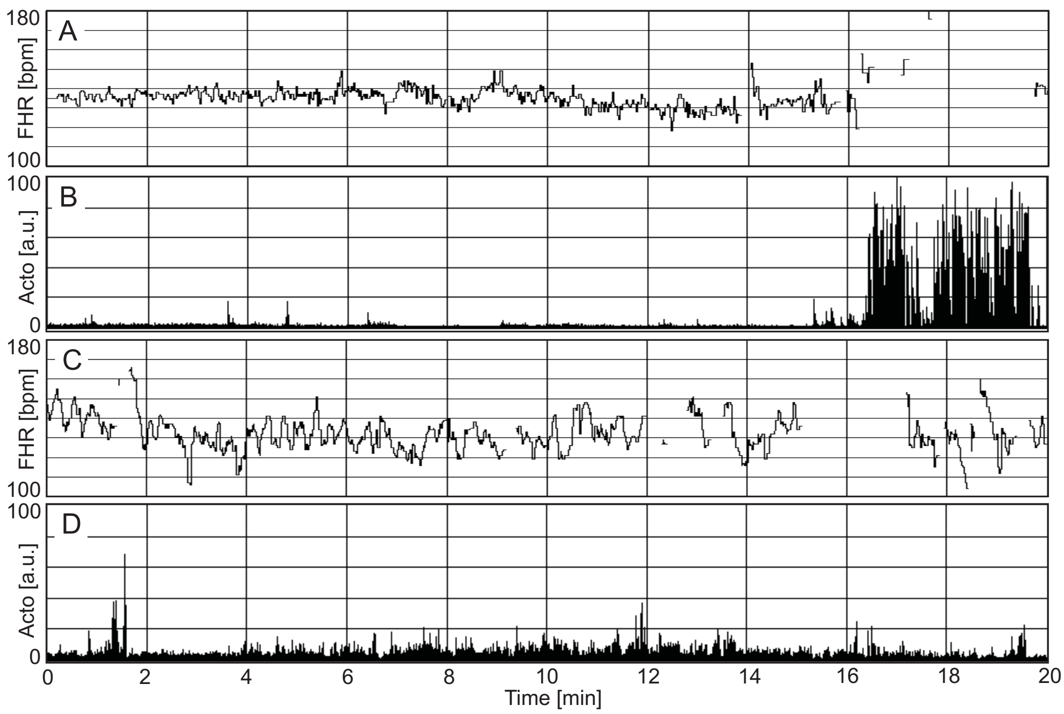

Fig. 3. Examples of the FHR signals (A and C) together with corresponding continuous actograms (B and D).

corresponding to the fetal movement episodes is unknown, the detection is carried out using an established minimum detection threshold (Minimum threshold). That takes place until the register is full, then the stored samples are sorted in ascending order, and the mean value from the established number of samples (refering to the percentage of a register size) from the higher side is calculated. For example, for the register storing 120 samples the number of 25% leads to calculation of the mean value over samples from positions: 91 to 120. The detection threshold is set as a half of the mean value, and when it is lower than the Minimum threshold, the latter one is set as a valid threshold level. In the next step, in one-second fragment of 231 samples being analysed, the number of samples exceeding the threshold level is calculated. When that number exceeds the Limit value this fragment is classified as the fetal movement episode the value of binary actogram = 1. The results obtained using this algorithm strongly depend on the initially set values of variables, and that will be showed in the next paragraph.

3. RESULTS AND DISCUSSION

At first, we tested the influence of Minimum threshold and Limit value on the algorithm efficiency was tested. Shift register length was set to 120 s, whereas the percentage of samples taking part in the threshold calculation was 25%. The value of the Minimum threshold was changed from 5 to 20 with step of 1, whereas the Limit value from 2 to 20 with step of 2. Those ranges were established empirically basing on visual assessment of the continuous actograms. The algorithm evaluation concerns its efficiency defined as both the number of movement episodes detected and their duration. The recognized movement episode was considered as correct when it had a common part with the reference movement or the shift between them was not more than 5 seconds. That was due the fact that the reference information on fetal movement activity provided by mother is not gold standard, but it is the only available reference information that can be obtained during routine monitoring session. Recognized episodes but not corresponding to the reference ones, were treated as incorrect. The durations of the correct and incorrect episodes were calculated. As it could be expected when the Minimum threshold and the Limit value were decreasing, the number of the correctly detected episodes was increasing from 36 to 135 for the boundary values of these variables, which relates to 25% and 95% of the 142 reference movements. The same tendency was observed for the number of the incorrect episodes (52-383), as well as for the duration of correct (114-621 s) and incorrect (72-3348 s) episodes of the fetal movement activity. Table 1 shows selected, specific levels of two variables established to obtain results as close as possible to the assumed levels of detection efficiency of correctly recognized movement episodes: 60%, 70%, 80%, 90% and 95%. The increase of the detection efficiency is accompanied by the increase of the other measures, and their biggest change is noted between cases 89% and 94%.

Although the number of correctly recognized movements increased only by 6 (efficiency by 5%), the number and duration of the incorrectly recognized episodes increased by 48 (40%)

Table 1. The selected results concerning automated recognition of the fetal movement activity using the developed algorithm, for which the detection efficiency of correctly recognized movement episodes corresponds as close as possible to the assumed values: 60%, 70%, 80%, 90% and 95%.

Minimum Threshold	Limit value	Number of episodes			Duration of episodes	
		correct		incorrect	correct	incorrect
12	20	87	(61%)	50	307	321
13	14	98	(69%)	62	351	389
12	10	114	(80%)	88	424	674
9	10	127	(89%)	120	492	994
10	4	133	(94%)	168	570	1689

and by 695 s respectively, which of course has an adverse impact on the algorithm efficiency. In general, more significant changes are observed when analyzing the movement durations. It is caused by the fact that even a slight shift between the location of movement detected in actogram and the marker from mother, provide a negative result. This in turn leads to bigger differences of the results in relation to the reference signal, than in the case of the analysis of the number of detected movements itself.

In the next stage, for the settings of Minimum threshold and Limit value presented in Table 1, two other parameters have been changing. Shift register length was being changed from 60 to 300 s with one-minute step, whereas the number of elements used for threshold calculation (determining the number of samples with the highest value and defined as a percentage of the register length) from 15% to 85% with step of 10%. Any changes in the shift register length and percentage of elements in the shift register used for threshold calculation did not improve the final results.

Final stage was the comparison of our new algorithm with a simple classical method popular in bedside monitors, where the constant threshold level is applied to continuous actogram. We tested 26 levels of threshold, from 5 to 30, in order to ensure a reliable comparison. The values of threshold level presented in Table 2 were selected to correspond as close as possible to the assumed values of the detection efficiency: 60%, 70%, 80%, 90% and 95% (just like in Table 1). As it can be noted, for the selected cases the proposed algorithm provided much better results: a lower number and duration of incorrectly detected movement episodes. The difference in values obtained for the two methods reached 26% and 33% for number of movements and their durations respectively.

Increase of the number of correctly detected movements was accompanied by an increase of the other measures, and their largest change is noted between cases 89% and 94% of detection efficiency. Although the number of correctly detected movements increased only by 6 (efficiency by 5%), the number and duration of incorrect episodes increased by 48 (40%) and by 695 seconds respectively, which has an adverse impact on the algorithm usability. It leads to conclusion that the algorithm provides the best results for the Minimum threshold set at 9 and Limit value equal to 10.

These settings ensure detection of up to 89% of movement perceived by mother, whereas the number and duration of incorrectly detected episodes correspond to 84% and 136% of the reference values respectively. Since pregnant woman is able to perceive only about 30% of fetal movements we can conclude that the movements detected by our algorithm, having no equivalent in maternal markers, may in fact represent episodes of true fetal movement activity. In [10] the authors, along with the fetal movements perceived by mother, registered also actograms using two different cardiotocographic monitors as well as ultrasonographic video recording, which was later interpreted by clinical experts in order to indicate all the reference episodes of fetal movement activity. The results obtained for a large database of 101 patients (86592 s, 3030 fetal movements) revealed that basing on the actogram the amount of actual fetal

Table 2. The selected results concerning automated recognition of the fetal movement activity using the constant threshold level, for which the detection efficiency of correctly detected movement episodes corresponds as close as possible to the assumed values: 60%, 70%, 80%, 90% and 95%.

Constant Threshold	Number of episodes		Duration of episodes	
	correct	incorrect	correct	incorrect
29	86 (60%)	64	290	361
26	98 (69%)	84	335	493
21	116 (81%)	116	432	816
17	127 (89%)	156	548	1263
11	135 (95%)	225	639	2522

movements detected was 57.52% (Corometrics 116; single transducer), 67.57% (Corometrics 116; two transducers), 41,98% (HP 1350-A). At the same time the mothers perceived only 37.92% of all movements. These results revealed that the automatic methods based on actogram analysis are characterized by higher (HP 1350-A) or much higher (Corometrics 116) sensitivity of movement detection compared to the maternal perception.

4. CONCLUSIONS

Analysis of the fetal movement activity is essential for the reliable interpretation of the cardiotocographic signals, as it allows detection of the nonreactive recordings. The actogram obtained by means of the Doppler ultrasound method has been more and more often used to assess the fetal movement activity, becoming an integral part of the cardiotocogram. In the presented study, we developed an algorithm for automated detection of this activity, which is to be implemented inside the monitoring instrumentation. The results of the algorithm were verified using fetal movement episodes perceived and marked by mother.

Taking maternal markers as reference information on the fetal movement activity is not the optimal solution. According to literature, mother is able to feel only a part of fetal movements, and additionally her reaction to fetal movements depends on her individual psycho-physical condition. Nevertheless, better reference information can be provided only by ultrasonic imaging. Unfortunately, this is a procedure that being carried out simultaneously with long-term cardiotocographic monitoring involves a highly qualified medical staff. In addition, its application is limited since the various ultrasound transducers may interfere, distorting the Doppler signal.

The method for obtaining binary information on fetal movement activity basing on continuous actogram representing its instantaneous intensity was proposed. This method takes into account that both the amplitude of the continuous actogram in fragments corresponding to movement activity, and the amplitude of background noise were significantly variable between individual recordings. Thus the threshold level was calculated at the initial stage of the procedure and was continuously adapted to actual actogram amplitude during the whole monitoring session. This approach in comparison to simple constant threshold technique ensured higher efficiency of recognition of the fetal movement episodes while minimizing the number of movements incorrectly detected, i.e. not corresponding to the fetal movements perceived by mother.

The presented study is a preliminary work on automated analysis of the fetal movement activity, and it was focused on analysis of the continuous actogram to obtain its binary representation. In our further investigations we expected to test the influence of different frequency bands of the Doppler signal on information content of the continuous actogram. In order to ensure the highest reliability of the results larger database of signals will be necessary.

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