electrical uterine activity,
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ANALYSIS OF ELECTRICAL UTERINE CONTRACTILE ACTIVITY FOR PREDICTION OF PRETERM DELIVERY

This study is aimed at evaluation of the capability to indicate the preterm delivery risk analysing the features extracted from signals of electrical uterine activity. Free access database was used with signals acquired in two groups of pregnant women who delivered at term and preterm. Signal features comprised classical time domain and spectral parameters of contractile activity, as well as the sample entropy. Their mean values were calculated over all contraction episodes detected in each record and their statistical significance for separating the two groups of recordings was provided. Influence of electrodes location, band-pass filter settings and gestation week was investigated. The obtained results showed that a spectral parameter – the median frequency was the most promising indicator of the preterm delivery risk.

1. INTRODUCTION

Preterm delivery is a main cause of neonatal deaths. In addition, a premature infant usually needs to be hospitalized in neonatal intensive care unit which leads to an increase of the healthcare costs. Therefore, early recognition of symptoms of preterm labour is very important in order to enable an effective treatment and to prolong a pregnancy period as close as possible to the predicted delivery term. As it has been confirmed in clinical practice, the classical external tocography is not sufficient for precise classification of patients at risk of preterm labour because this method measures only the mechanical effects of the contractile activity [10], [15]. Since each uterine contraction must be preceded by electrical excitation which arises and then propagates through a uterine muscle, monitoring of the electrical uterine activity accomplished by electrohysterography (EHG) seems to be the only potential solution to solve this problem [2], [12]. So far, many studies have been aimed mainly at application of EHG as alternative to tocography for the fetal state assessment and controlling the labour progress [7].

The EHG signal can be modelled as an action potentials fast wave whose amplitude is modulated by a slow wave corresponding to the contractions frequency [9]. Thus, when analysing the electrohysterogram, not only the time domain parameters used for classical description of contraction episodes, but also a number of frequency based parameters can be determined [1].

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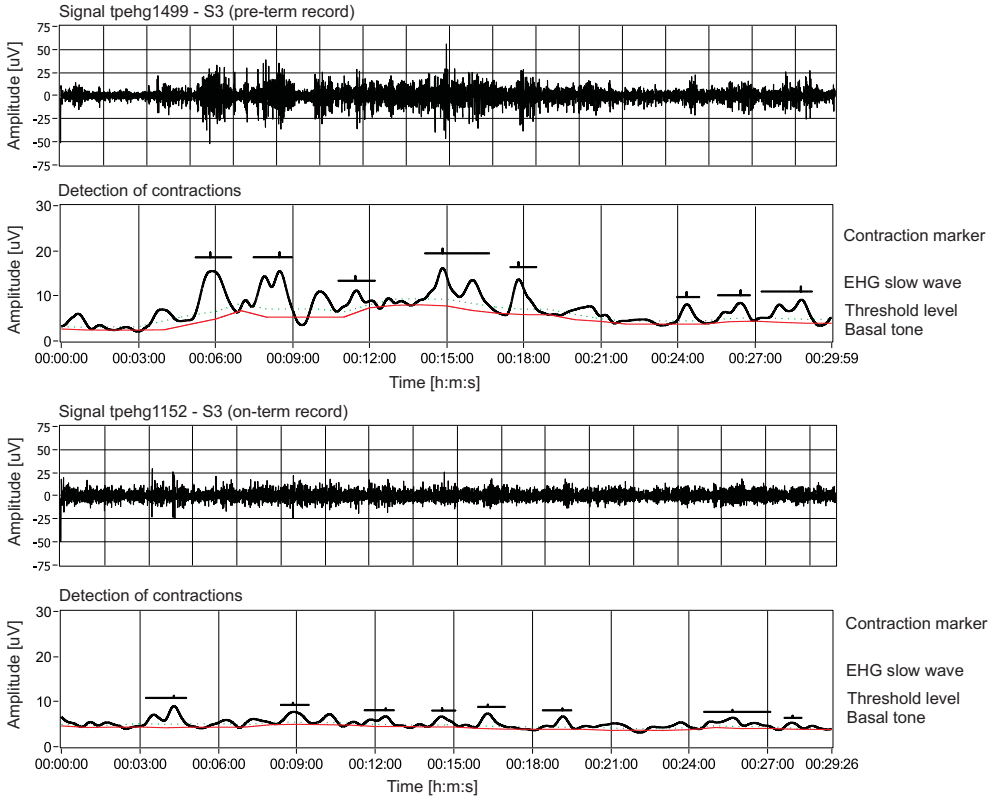

Fig. 1. The exemplary two electrohysterograms from the preterm and full-term groups with determined envelope and detected contractile segments. Horizontal line corresponds to contraction duration, whereas vertical marker shows the maximum amplitude.

Estimation of their efficiency to differentiate between EHG signals recorded from pregnancy ended at term and prematurely was the aim of our investigations.

2. METHODS

Research material has been obtained through the Physionet.org platform, which gives free access to many databases of biophysical signals [5]. We used the database from [4] with the 300 EHG recordings grouped as follows:

A. *Full-term* group comprising 262 electrohysterograms from pregnancy ended with delivery during or after the 37^{th} week of gestation, which is divided into two subgroups with:
   I. 143 *early* recordings - acquired before the 26^{th} week of gestation;
   II. 119 *late* recordings - acquired during or after the 26^{th} week.

B. *Preterm* group comprising 38 electrohysterograms from pregnancy ended prematurely i.e. before the 37^{th} week, which is divided into the same two subgroups with:
   I. 19 *early* recordings;
   II. 19 *late* recordings.

The signals were recorded by means of four electrodes placed on abdominal wall over an upper part of the uterine muscle to form the square of seven centimetres side. Three differential channels were constituted by: top (S1) and bottom (S3) horizontal pairs of electrodes, and right vertical pair (S2). Each signal underwent preprocessing which relied on band-pass filtering in three different frequency bands: F1 = $0.08 \div 4$ Hz, F2 = $0.3 \div 4$ Hz and F3 = $0.3 \div 3$ Hz.

Uterine contractile activity is reflected in electrohysterogram by the bursts of action potential spikes, which occur synchronically with the contraction periods observed in the mechanical

signal being simultaneously recorded by a strain-gauge transducer attached to maternal abdomen [3], [14]. The procedure for identification of contractile episodes was applied to each recording [8]. The algorithm consists of the following steps: determination of the EHG envelope which represents the strength of contractile activity, determination of the so called basal tone which corresponds to the resting potential, selection of threshold level to identify the episodes of increased activity and their classification as contractions when duration and amplitude in relation to the basal tone exceed the established minimal values. Each detected contraction is represented by the onset time (T_S), when the EHG envelope crosses the threshold level and duration (T_D) defining the time when the envelope remains above the threshold level. These timing markers enable to extract uterine contractile segments from EHG signals for determination of the contraction features.

2.1. TIME DOMAIN PARAMETERS

In the contraction curve (the envelope obtained from the electrical activity signal or the signal of mechanical activity) the contraction is described by the duration, amplitude as well as the area under curve, which stretches between the envelope curve and the basal tone. The root mean square RMS is calculated for each *j*-th contractile activity episode detected in EHG signal:

$$RMS_j = \sqrt{\frac{1}{C}\sum_{i=T_{Sj}f_S}^{C} x_i^2} \quad where \quad C = (T_{Sj} + T_{Dj})f_S \tag{1}$$

where: T_{Sj} is the onset time of the *j*-th contraction, T_{Dj} its duration and f_S is the sampling frequency. Then mean value over RMS values obtained for all detected contractile episodes is representative feature of a given EHG signal.

2.2. SPECTRAL PARAMETERS

The power spectrum density (PSD) is determined for every burst of action potential spikes in EHG signal that corresponds to contractile activity identified in the envelope [7]. Contraction power is calculated as a sum of amplitudes of frequency components of PSD multiplied by the frequency resolution:

$$P = \sum_{i=L}^{H}(p_i \cdot \frac{f_S}{N}) \tag{2}$$

where: p_i is the amplitude of *i*-th PSD component, H and L are the number of PSD component corresponding to the upper and lower limit of the EHG frequency band, f_S is the sampling frequency and N is a number of samples.

Maximum power frequency indicates the component in PSD of the maximum power (amplitude):

$$F_{max} = k\frac{f_S}{N} \quad \rightarrow \quad p_k = max(p_1 \ldots p_M) \tag{3}$$

where: k is the k-th PSD component, f_S is the sampling frequency, N is a number of samples and M is a number of frequency components in PSD (for the single-sided PSD the $M = N/2$).

Median frequency represents the component frequency which split the PSD into two parts of the same power:

$$F_{med} = k\frac{f_S}{N} \quad \rightarrow \quad \sum_{i=1}^{k} p_i = \sum_{i=k}^{M} p_i \tag{4}$$

Mean frequency is calculated as:

$$F_{mean} = \frac{\sum_{i=1}^{M} f_i p_i}{\sum_{i=1}^{M} p_i} \tag{5}$$

where: f_i is the value of the frequency and p_i is the amplitude of PSD component corresponding to this frequency.

2.3. SAMPLE ENTROPY

For a time series of N points, x_1, x_2, . . . , x_N, we define subsequences, also called template vectors of length m, given by: $y_i(m) = (x_i, x_{i+1}, \cdot, x_{i+m-1})$ where $i = 1, 2, \cdot, N - m + 1$. Then the following quantity is defined: $B_i^m(r)$ as $(N - m - 1)^{-1}$ times the number of vectors X_j^m within r of X_i^m, where j ranges from 1 to $N - m$, and $j \neq i$ to exclude self-matches, and then define:

$$B^m(r) = \frac{1}{N-m} \sum_{i=1}^{N-m} B_i^m(r) \tag{6}$$

Similarly, we define $A_i^m(r)$ as $(N - m - 1)^{-1}$ times the number of vectors X_j^{m+1} within r of X_i^{m+1}, where j ranges from 1 to $N - m$, where $j \neq i$, and then:

$$A^m(r) = \frac{1}{N-m} \sum_{i=1}^{N-m} A_i^m(r) \tag{7}$$

The parameter *SampEn (m,r)* is then defined as $lim_{N\to\infty}\{-ln\,[A^m(r)/B^m(r)]\}$, which can be estimated by the statistic [13]:

$$SampEn(m, r, N) = -ln\,[A^m(r)/B^m(r)] \tag{8}$$

where: N is the length of the time series, m is the length of sequences to be compared, and r is the tolerance for accepting matches. Although r and m are critical in determining the outcome of the sample entropy estimation, no guidelines exist for optimizing their values [17]. Thus we applied the values provided in [11], where r is set to 0.2 and m is set to 1.

3. RESULTS

In the recordings from group A (*full-term*) we detected about 1800 contractile episodes, whereas in group B (*preterm*) we extracted over 260. Mean number of contractions per recording was about 7. The detailed results are listed in Table 1.

Each of nine combinations of EHG signals (three channels and three optional filtering) for each of the 300 recordings was represented by the values of nine features described in the *Methods* section. Each feature was represented by the mean calculated over the values obtained only for the episodes of contractile activity detected in a given signal. Finally, we obtained 3 (S1÷S3) x 3 (F1÷F3) x 9 features = 81 descriptive values for each of 300 recordings in order to evaluate the particular feature ability to differentiate between full-term A and preterm B the EHG recordings. The evaluation was performed by means of Student's t-test

Table 1. Results of contractile activity detection for particular groups, channels and frequency bands.

Group	F1			F2			F3		
	S1	S2	S3	S1	S2	S3	S1	S2	S3
A.I	999/7.0#	995/7.0	979/6.9	962/6.7	955/6.7	968/6.8	963/6.7	948/6.6	963/6.7
A.II	881/7.4	880/7.4	873/7.3	827/7.0	846/7.1	820/6.9	831/7.0	850/7.1	821/6.9
B.I	137/7.1	143/7.5	137/7.2	131/6.9	128/6.7	136/7.1	132/7.0	129/6.8	137/7.2
B.II	144/7.6	147/7.7	139/7.3	132/7.0	139/7.3	125/6.6	131/6.9	140/7.4	124/6.5

total number of detected contractile episodes / mean number per record

Table 2. Statistical significance of the contractile episode features obtained in the group of all recordings. Statistically significant differences ($p < 0.05$) between A and B are distinguished.

		F1		F2		F3	
		A	B	A	B	A	B
$Duration[s]$	S1	86.5	83.3	89.3	90.7	88.7	91.1
	S2	84.9	82.2	89.6	86.3	89.6	85.7
	S3	84.5	85.4	88.4	90.9	88.5	90.4
$Amplitude[\mu V]$	S1	13.7	13.8	4.7	4.8	4.6	4.7
	S2	14.6	13.3	5.0	4.8	4.9	4.7
	S3	10.2	10.9	3.5	3.6	3.5	3.6
$Area[\mu V \cdot s]$	S1	678.0	659.6	230.8	240.7	225.3	235.4
	S2	715.8	630.3	242.0	234.9	241.4	231.9
	S3	487.0	537.7	164.0	181.9	162.2	177.9
$RMS[\mu V]$	S1	18.5	18.3	7.3	7.1	7.5	7.4
	S2	18.0	16.9	6.7	6.6	6.8	6.7
	S3	13.5	14.1	5.2	5.3	5.4	5.4
$Power[\mu V^2]$	S1	351.2	231.0	71.9	33.5	76.4	34.9
	S2	499.2	212.0	106.4	30.8	109.6	31.5
	S3	223.3	123.9	45.4	19.0	47.6	20.0
$Fmax[Hz]$	S1	0.17	0.17	0.55	0.50	0.56	0.51
	S2	0.14	0.14	0.42	0.40	0.42	0.40
	S3	0.15	0.15	#0.50	0.42	∗#0.52	0.42
$F_{med}[Hz]$	S1	0.22	0.21	∗#0.60	0.53	∗#0.67	0.59
	S2	0.18	0.18	0.50	0.49	0.53	0.52
	S3	0.19	0.19	#0.58	0.49	#0.64	0.53
$F_{mean}[Hz]$	S1	0.36	0.32	0.78	0.73	0.96	0.89
	S2	0.27	0.28	0.66	0.65	0.75	0.73
	S3	0.32	0.29	#0.76	0.67	#0.93	0.80
$SampEn.$	S1	∗0.80	0.77	∗0.54	0.53	0.73	0.71
	S2	0.59	0.58	0.41	0.42	0.54	0.54
	S3	∗0.65	0.62	∗0.40	0.39	∗0.59	0.56

indicating significant difference ($p < 0.05$)

∗ reported also in [4] as statistically significant ($p < 0.05$)

with significance level $p \leq 0.05$. The distribution of feature sets was not significantly different from normal distribution which was confirmed by Shapiro-Wilk test. Complete results obtained for all recordings are presented in Table 2. The next two tables present separately the results obtained for the recordings acquired before the 26^{th} week of gestation (Table 3), and during or after that week (Table 4). These tables list only these signal combinations for which the noticeable differences were found between the groups A.I and B.I (Table 3), as well as A.II and B.II (Table 4).

The same features that have been reported in [4] as being able to differentiate the EHG recordings with statistical significance ($p \leq 0.05$) in particular groups, are specially marked in the tables. However it should be strongly underlined that in [4] the features were calculated for entire signals.

In general, among different features that were determined for the EHG signals with the contractile activity episodes, the spectral parameters (maximum power, median and mean frequencies for all groups, and power for the recordings $< 26^{th}$ week) have been found as

Table 3. The features determined in the group of the recordings $< 26^{th}$ week, which indicate significant difference between A.I and B.I ($p < 0.05$) for a given combination of signal and filtering.

	A.I	B.I
$Area(F1, S2)$	607.7	459.5
$Power(F1, S2)$	219.2	134.7
$F_{max}(F1, S2)$	0.15	0.13
$F_{max}(F2, S3)$	0.53	0.45
$F_{med}(F2, S3)$	0.62	0.50
$F_{mean}(F2, S3)$	0.81	0.69
$F_{max}(F3, S3)$	0.57	0.44
$F_{med}(F3, S3)^*$	0.70	0.53
$F_{mean}(F3, S3)$	1.00	0.82

* reported also in [4] as statistically significant ($p < 0.05$)

Table 4. The features determined in the group of the recordings $\geq 26^{th}$ week, which indicate significant difference between A.I and B.I ($p < 0.05$) for a given combination of signal and filtering.

	A.II	B.II
$F_{med}(F1, S2)$	0.18	0.20
$F_{max}(F2, S3)$	0.46	0.39
$F_{med}(F2, S1)$	0.55	0.48
$F_{med}(F2, S3)$	0.53	0.48
$F_{max}(F3, S3)$	0.46	0.40
$F_{med}(F3, S1)$	0.59	0.52

the only ones that can efficiently differentiate between the preterm and full-term recordings. Such ability was noted for the contractile activity area but only for early period of pregnancy.

The values of SampEn reported in [4], as indicating the significant difference between preterm and full-term signals, does not show such ability in our study when the sample entropy was calculated for the contractile episodes only. When analysing the influence of the signal channel selection on the spectral features efficiency, we can state that the best results are provided by bottom horizontal pair of electrodes (S3). It is clearly seen in Table 2, and it is expressed by the high number of the features obtained for this signal presented in Table 3 and Table 4. It can be also noted that the features of the signals from early period of pregnancy are more capable to differentiate the predicted full-term and the preterm delivery than those from the late period.

As for the frequency bands, a narrowing of the signal band led to improvement of the ability to differentiate the EHG signals. For the widest band none of the features indicated significant differences between group A and B. When analysing the early and late recordings separately that widest band has been useful for power, area and maximum frequency.

4. CONCLUSIONS

The result obtained in this paper showed that spectral features of EHG signals, and among them especially the median frequency, have the best efficiency to distinguish the recordings with symptoms of threatening preterm delivery from those acquired during the full-term pregnancy. More features of the signals from early period of pregnancy than from the late period have been found as capable to differentiate the full-term and the preterm delivery. We noticed that the higher efficiency was obtained for the EHG signals after filtering in narrower frequency bands (0.3÷4 Hz and 0.3÷3 Hz) and when they were recorded from electrodes placed on the bottom part and aligned horizontally. The latter is probably connected with the fact that when the electrical excitation propagates from top to bottom part of uterine muscle, then more and more uterine muscle cells are involved in contraction [6]. The sample entropy may be associated with time of delivery when it is calculated for whole electrohysterograms as it was proved in

[4], but it does not show such ability when it is calculated for contraction activity segments only. Our study did not confirm the results reported in [16] that RMS value could be a sign of physiological characteristics of women prone to preterm labour. The main task to apply the electrohysterography as useful clinical tool is indication of the symptoms of preterm labour. Thus, in the light of the obtained results further study have to be conducted with considering other measures of contractile activity mostly in the frequency domain, and with testing other numbers and locations of electrodes.

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