ABSTRACT

In respect to the main goal of our ongoing work for predicting preterm birth, we analyze in this paper uterine EMG recordings of 11 pregnant and laboring women by means of Detrended Fluctuation Analysis (DFA), a scaling analysis method that quantifies a simple parameter to represent the correlation properties of a time series. Our study provides convincing evidence that pregnancy progress is typically associated to an alteration in the long-range correlation of the uterine EMG recordings. The results obtained from the analyzed data indicate that the correlation in the contractions increases during pregnancy. Furthermore, we demonstrate that the long-range parameter may discriminate between the two classes (pregnancy/labor). The results are supported by statistical analysis using t-test indicating good statistical significance with a confidence level of 95%. A surrogate data test is also performed to investigate the nature of the underlying dynamics of our experimental data. The results are very promising for monitoring pregnancy and detecting labor and may help identify preterm labor.

I. INTRODUCTION

Uterine electromyography (EMG) is a promising technique for monitoring the uterine activity, based on recording the electrical activity of the uterus from the abdominal wall of pregnant women [1, 2]. It has been proved that it is of interest to offer a good insight into the process of pregnancy and labor [3, 4]. Furthermore, uterine EMG was investigated in order to predict the risk of preterm labor and subsequent preterm birth [5, 6]. Today, temporal and spectral characteristics of the uterine EMG were defined in two physiological states: pregnancy and parturition. Some of these characteristics have been proposed to monitor pregnancy and detect labor. However, such measures offer little insight into the underlying dynamics of the physiological system of the uterus. In order to develop a rational approach towards improving true labor detection, a thorough understanding of the mechanism by which labor is initiated is important. Therefore, monitoring and analyzing contractions during pregnancy through steps leading to labor is essential. There may be a pattern in the uterine contractions or in its long-range correlation that can reveal whether or not a contraction will lead to a delivery. Nonlinear dynamical analysis of uterine contraction signals can therefore provide information regarding physiological changes during pregnancy [7, 8]. A promising technique for this purpose is the detrended fluctuation analysis (DFA). DFA, which was first introduced by Peng et al. [9] for the aim of analyzing physiological time series, is a signal analysis method that provides a scaling exponent alpha (α) which gives information concerning the correlation properties of the signal. This technique is used to identify hidden dynamical patterns, which would yield important insights into underlying physiological mechanisms. Therefore, it suits the study of power-law long-range correlation present in a variety of non-stationary time series. The main advantage of the DFA is that this method can systematically eliminate trends of various order caused by external effects. In that way, it can reduce noise caused by imperfect measurement. The DFA method has been successfully applied to detect long-range correlations in complex physiological signals such as Electrocardiograms [10], human brain electroencephalogram [11], and human postural sway data [12].

The aims of this paper are twofold: firstly, we apply DFA on uterine EMG signals recorded on women at different increasing pregnancy terms to assess differences in uterine EMG dynamics throughout pregnancy and at the onset of labor. Secondly, we investigate whether DFA may discriminate the two conditions by applying this technique on signals chosen randomly from the two classes of contractions (pregnancy, labor).

II. MATERIALS AND METHODS

A. Data

Our analysis in this paper is based on digitized uterine EMG signals recorded on 11 women: 5 recorded during pregnancy (33 – 39 week...
Let $V_{bi}$ represent the derived bipolar signals. Polynomials can be used in the fitting procedure. The fitting normally used although quadratic, cubic, or higher order interpolate the sequence in each box. A linear fit (i.e. each box of length $\frac{N}{5}$ have a standard deviation of $1^{14}$. A trace was digitized to ease the segmentation of the bursts [13]. The simultaneous tocodynamometer paper frequency of 100 Hz. The simultaneous tocodynamometer paper. The recording device has an anti-aliasing filter with a cut-off noise ratio on all bipolar channels. Signals were sampled at 200 Hz. Rectangular 3x4 matrix. All the bursts presented a good signal to noise ratio. Our signals form thus a grid, arranged in a 4x4 matrix positioned on the women’s abdomen (VSN 02-0006-V2). They were performed by using a 16 electrode Iceland, by using a protocol approved by the ethical committee pregnancy contractions. The measurements were made at the Landspitali University hospital in Iceland and FSA Akureyi, Iceland, by using a protocol approved by the ethical committee (VSN 02-0006-V2). They were performed by using a 16 electrode grid, arranged in a 4x4 matrix positioned on the women’s abdomen (Fig.1). In this study, we considered vertical bipolar signals (Vbi) in order to increase the signal to noise ratio. Our signals form thus a rectangular 3x4 matrix. All the bursts presented a good signal to noise ratio on all bipolar channels. Signals were sampled at 200 Hz. The recording device has an anti-aliasing filter with a cut-off frequency of 100 Hz. The simultaneous tocodynamometer paper trace was digitized to ease the segmentation of the bursts [13]. Throughout this work, all contractions have been normalized to have a standard deviation of $1^{14}$. In order to increase the signal to noise ratio. Our signals form thus a grid, arranged in a 4x4 matrix positioned on the women’s abdomen (VSN 02-0006-V2). They were performed by using a 16 electrode Iceland, by using a protocol approved by the ethical committee pregnancy contractions. The measurements were made at the Landspitali University hospital in Iceland and FSA Akureyi, Iceland, by using a protocol approved by the ethical committee (VSN 02-0006-V2). They were performed by using a 16 electrode grid, arranged in a 4x4 matrix positioned on the women’s abdomen (Fig.1). In this study, we considered vertical bipolar signals (Vbi) in order to increase the signal to noise ratio. Our signals form thus a rectangular 3x4 matrix. All the bursts presented a good signal to noise ratio on all bipolar channels. Signals were sampled at 200 Hz. The recording device has an anti-aliasing filter with a cut-off frequency of 100 Hz. The simultaneous tocodynamometer paper trace was digitized to ease the segmentation of the bursts [13].

**B. Detrended Fluctuation Analysis:**

Let $x(i)$ be the time series of total length $N$ whose fluctuations are to be studied. The method consists initially in obtaining from the original series $x(i)$ a new integrated series $y(k)$ as

$$y(k) = \sum_{i=1}^{k} [x(i) - \bar{x}]$$

Where,

$$\bar{x} = \frac{1}{N} \sum_{i=1}^{N} x(i)$$

Next, the time series is divided into boxes of equal length $n$. In each box of length $n$, a polynomial function of degree $m$ is used to interpolate the sequence in each box. A linear fit (i.e. $m=1$) is normally used although quadratic, cubic, or higher order polynomials can be used in the fitting procedure. The fitting polynomial $y_m(k)$ represents the local trend in each box. Next, the local trend of each window is subtracted from the integrated series. The fluctuation function $F(n)$ is then calculated as the root-mean square of the detrended time series as a function of the box size $n$.

$$F(n) = \sqrt{\frac{1}{N} \sum_{k=1}^{N} (y(k) - y_m(k))^2}$$

This procedure is repeated for a broad range of segments lengths $n$. According to Peng et al. [9], the following range $n_{min}=5$ and $n_{max}=N/4$ should be selected. Typically, $F(n)$ increases with the box size $n$. Under such conditions, if the time series is self-similar, a relationship indicates the presence of power law scaling $F(n) \sim n^\alpha$. The scaling exponent $\alpha$ can be estimated by a linear fit on the log–log plot of $F(n)$ versus $n$. The value of $\alpha$ represents the correlation properties of the time series.

The scaling exponent may have different values: for the uncorrelated data (i.e. white noise), $\alpha=0.5$. An $\alpha$ smaller than 0.5 indicates that the correlations in the signal are anti-persistent (i.e. an increment is very likely to be followed by a decrement, and vice versa), while an $\alpha>0.5$ indicates that the correlations in the signal are persistent (i.e. an increment is very likely to be followed by an increment). The values $\alpha=1$ and $\alpha=1.5$ correspond to $1/f$-noise and Brownian motion, respectively. A value $\alpha>1.5$ corresponds to long-range correlations that are not necessarily related to stochastic processes.

**C. Surrogate data tests**

While applying nonlinear techniques to study dynamic phenomena, it is important to question if the data requires such a complicated procedure. Although in most cases natural processes are considered nonlinear, this may not be clearly reflected in recorded data. Surrogate data are designed to study if the use of nonlinear analysis techniques is necessary. Significant differences between original and surrogate data, when compared by means of any nonlinear statistics, indicate the existence of nonlinearities in the data [15]. Therefore, the uterine EMG recordings are tested for nonlinearity using surrogate data analysis. The surrogate data were generated by first computing the Fourier transforms of the original signals, randomizing the Fourier phase while preserving the moduli, and then performing inverse Fourier transforms. Surrogate data have amplitude spectra identical to the original signals, but possible temporal correlations are destroyed. Thirty surrogate data were generated to match each original data used. The scaling exponents of DFA are computed for both original data and surrogate data. In order to measure quantitatively the difference between the original data and the surrogates, we compute the $z$ score value:

$$z = \frac{|\alpha_{org} - <\alpha_{surr}>|}{\sigma_{surr}}$$

Where $\alpha_{org}$ denotes the value of the scaling exponent for the original dataset and $<\alpha_{surr}>$ denotes the mean value of the scaling exponent of the surrogate data and $\sigma_{surr}$ its standard deviation.

**III. RESULTS**

First, we studied the temporal evolution of the scaling exponent $\alpha$ calculated by the DFA method throughout pregnancy. We used the data recorded on two women (W1 and W2) at two and three increasing pregnancy terms respectively. First, we compute the
scaling exponent $\alpha$ over all the bipolar signals ($V_{bi}$, $i=1-12$) related to each contraction. Then we determine their average over all the contractions during the following recording sessions: 2 contractions at 30 WG (G1) and 2 contractions at 32 WG (G2) for the first women W1 and 4 contractions at 33 WG (G1’), 2 contractions at 35 WG (G2’) and 3 contractions at 37 WG (G3’) for the second woman W2. The mean value of the scaling exponent $\alpha$ is determined for each woman at each term and plotted against the woman’s weeks of gestation interval (fig.2). The results show that the scaling exponent values change along gestation: we can evidence an obvious longitudinal evolution of the values of the scaling exponent throughout pregnancy.

Furthermore, our study was accomplished by investigating whether these values undergo changes from pregnancy to labor. We studied 30 contractions randomly chosen for each class: one class of 5 women recorded during pregnancy (32 – 39 WG) and the other of 6 women recorded during labor (39 - 42 WG). The same procedure for calculating the values of the scaling exponent was performed for each studied contraction. The results are illustrated in fig.3. Here also, the scaling exponent was greater for pregnancy than during labor.

Furthermore, in order to test the non-linearity in the original uterine EMG signals, we compared the scaling exponents of the original data of each class with those of the corresponding surrogate data. The values of the scaling exponent indicated low $z$ score during pregnancy and high values during labor (table 1). This means that contractions recorded during labor present a much stronger nonlinear character than the ones recorded during pregnancy and that the null hypothesis of a linear data can be rejected.

<table>
<thead>
<tr>
<th>Term</th>
<th>Original data</th>
<th>Surrogate data</th>
<th>$z$ score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Pregnancy</td>
<td>0.489±0.045</td>
<td>0.54±0.025</td>
<td>2.04</td>
</tr>
<tr>
<td>Labor</td>
<td>0.363±0.085</td>
<td>0.53±0.023</td>
<td>7.26</td>
</tr>
</tbody>
</table>

Table 1 – the scaling exponents of detrended fluctuation analysis of uterine EMG signals corresponding to the two classes (pregnancy, labor) and surrogate data.

**IV. DISCUSSION**

In this study, we analyzed uterine EMG recordings of 11 pregnant women by means of DFA, a scaling analysis method that quantifies a simple parameter to represent the correlation properties of a time series. The scaling exponent, the result of DFA, provides a quantitative measure of long range correlation that exists in the uterine EMG recordings. The scaling behavior in complex systems is interesting because it provides an intrinsic description of the systems; therefore, it gives a new insight into the activity of the uterus during pregnancy and labor. The present study demonstrates that, during pregnancy, the mean value of the scaling exponent calculated over our data signals was 0.489±0.045, which is referred to an uncorrelated time series [9]. We also noticed that, throughout pregnancy, the values of the scaling exponent decrease and follow an obvious longitudinal evolution (fig.2). Additionally, noticeable differences of the values of the scaling exponent of the uterine EMG signals that originate from pregnancy and laboring patients were noticed (fig.3).

One possible explanation of the decrease in the values of the scaling exponent is that, during pregnancy, the uterine activity is weak and localized. The propagation is also limited. This condition favors quiescence of the myometrium and is essential for the maintenance of the pregnancy to ensure successful maturation of the fetus [1, 2, 3, 4, 5, 6, 16]. At labor, however, when the fetus is fully developed, the synchronization in the uterus is stronger. The uterus exhibits rhythmic forceful contractions. Therefore, the contractions become more and more frequent and increase in strength. The uterine activity is considered to be fully propagated through the whole uterus and the uterine contractions become more coordinated [17]. Hence, a long-range correlation in the recordings may be expected. Also, our study shows that the physical property of long-term correlation is actually a parameter suitable in some cases for pregnancy monitoring and labor identification. The results obtained indicate that the long-range correlation can distinguish pregnancy and labor contractions with more than 95% confidence (using $t$-test).

**V. CONCLUSION**

To gain a further insight into the underlying dynamics of the physiological system of the uterus, the detrended fluctuation analysis (DFA) of uterine EMG is described. Our study demonstrates that the scaling exponent, the result of DFA, gradually changes during pregnancy, that is, the long-range correlation in uterine contractions changes throughout pregnancy. We reported that the correlation in the contractions increases during pregnancy and is higher during labor. We showed that the scaling exponent is a promising way for pregnancy monitoring and labor detection. Thus, it was concluded that labor is not a direct transition from an inactive to an active state of the uterus. Finally, the results may help improve our understanding of the progression of pregnancy as well as how labor is initiated.
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REFERENCES