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Uterine contraction signals—Application of the linear synchronization measures

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ABSTRACT

Objective: In physiological research, there are not too many studies on multivariate data sets, containing two or more simultaneously recorded time series. It is important to examine synchronization in these kinds of signals. The aim of this study is to present the linear measures: the cross-correlation function, the coherence function, the wavelet cross-correlation and the wavelet coherence to assess synchronization between contractions in different topographic regions of the uterus.
Study design: Spontaneous uterine activity was recorded directly by a dual micro-tip catheter (Millar Instruments, Inc., USA). The device consisted of two ultra-miniature pressure sensors. One sensor was placed in the fundus, the other one in the cervix. For this analysis, a healthy patient with normal contractions, a patient with dysmenorrhea, a patient with fibromyomas in the follicular phase, and the patient with endometriosis were selected.
Results: For each method the values of synchronization parameters for normal contractions were higher than the values of these parameters for other pairs of signals. The differences between these four groups of the uterine contraction signals were clear. The lowest values of the synchronization measures were in the case of dysmenorrheic patient.
Conclusion: The analysis of synchronization of the uterine contractions signals may have a diagnostic value. For intrauterine pressure signals results obtained by means of different synchronization methods are different, but consistent.

1. Introduction

The word "synchronous" originates from the Greek words $\sigma\acute{\upsilon}\nu$ (syn = meaning the same, common) and $\chi\rho\acute{o}\nu o\zeta$ (chronos = meaning time), in direct translation "synchronous" means "sharing the same time". Synchronization phenomenon was first observed and described in the 17th century by Christian Huygens, a Dutch researcher [1–3]. He discovered that the rhythm of two pendulum clocks hanging from a common support was synchronized, i.e., their oscillations coincided perfectly. Adjustment of rhythms of oscillating objects due to an interaction among them is the essence of synchronization. It is not a state but complex dynamical process. In this paper the notion of synchronization will be used in a loose sense as a synonym of correlation. This term refers to a variety of phenomena in all branches of natural science, engineering and social life.

In physiological research, we often study multivariate data sets, containing two or more simultaneously recorded time series. It is important to examine synchronization in these kinds of signals. There is need to develop methods of recording uterine activity as well as mathematical interpretation of recorded time series.

The human uterus is indubitably a complex system where billions of cells comprising the myometrium interact in a complex manner. Our understanding of the co-ordination of the uterine contractions is incomplete. In our earlier papers, we presented linear (cross-correlation, semblance) and non-linear (mutual information) measures to identify time delays between contractions in different topographic regions of the uterus [4,5]. On the assumption that the reference signal is from the fundus, the various kinds of propagation of the contractions: the normal propagation, the inverted propagation and the simultaneous propagation may be observed. These measures were computed in a moving window with a width corresponding to approximately two or three contractions. As a result, the running synchronization functions were obtained. We introduced a propagation % parameter, which shows the percentage of normal contractions (normal propagation) during the investigated signals. The running synchronization functions visualize changes in the propagation of the two simultaneously recorded signals. They are very attractive methods and could be used to investigate various kinds of simultaneously recorded physiological time series. The results of the analyses were presented in the form of two-dimensional

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functions. The choice of the parameters (the width of the running window and the length of time shift) was very important and difficult. It had significant influence on the results. In order to describe similarity between the two signals we can use a simpler approach.

The aim of this study is to present the linear measures: the cross-correlation function, the coherence function, the wavelet cross-correlation, and the wavelet coherence to assess synchronization between contractions in different topographic regions of the uterus.

2. Materials and methods

2.1. Data acquisition and subjects

Spontaneous uterine activity in the non-pregnant states during the menstrual cycle was recorded by a micro-tip catheter (Millar Instruments, Inc., USA). Department of Pathophysiology of Pregnancy (Medical University of Bialystok) received local Ethic Committee approval, and all patients gave informed consent. The device consisted of two ultra-miniature pressure sensors. One sensor was placed in the fundus, the other one in the cervix. The distance between sensors was 30 mm. The sensors produced electrical signals, which varied in direct proportion to the magnitude of sensed pressures. After amplification analogue signals were passed to a personal computer for conversion to digital form by means of an analogue–digital (A/D) converter. The sampling frequency was 2 Hz. For the analysis of the recorded signals we used programs written in MATLAB (Math Works, Inc., USA) a high-performance language for technical computing. We also used Signal Processing Toolbox and Wavelet Toolbox with Matlab.

For our analysis, a healthy patient with normal contractions, a patient with dysmenorrhea, a patient with fibromyomas in the follicular phase, and the patient with endometriosis were selected.

2.2. Computational methods

In the investigated signals the original sampling frequency rate was reduced from 2 Hz to a lower rate of 1 Hz. We analysed four pairs of the uterine contraction signals. The mean and linear trend was removed. The signals were multiplied by hamming window and filtered with low-pass and high-pass filters [6]. By means of the Fourier analysis the dominant frequency (the frequency at which most signal energy was transmitted) was assessed for each time series [7]. We used the hamming window only for Fourier analysis.

In the case of wavelet analysis we used discrete wavelet transform (DWT). The level of performed discrete wavelet transform was from 7 to 9. In the case of the level equaling 7, we reconstructed approximation signal A7 and details Dj ($1 \leq j \leq 7$). The resulting seven wavelet decompositions represent the following frequency bands (from D1 to D7): 0.25–0.5 Hz; 0.125–0.25 Hz; 0.0625–0.125 Hz; 0.03125–0.0625 Hz; 0.015625–0.031125 Hz; 0.0078125–0.015625 Hz; 0.00390625–0.0078125 Hz. They are equivalent to following period bands: 2–4 s; 4–8 s; 8–16 s; 16–32 s; 32–64 s; 64–128 s; 128–256 s.

2.2.1. Cross-correlation function

The cross-correlation function gives the correlation degree between the two signals [4,5,8–10]. This function is a measure of linear synchronization between two time series. The cross-correlation function of the two discrete time series $x(n)$ and $y(n)$ is a statistical quantity defined as

$$\phi_{x,y}(l) = E[x(n)y(n+l)]$$

where E[ ] is the expected value operator, l is lag. Signals $x(n)$ and $y(n)$ are from the fundal and cervical sensors, respectively.

After normalization, the value of cross-correlation parameters will be between −1 and 1. The result is 1 when $x(n) = y(n)$ and $l = 0$, and it is −1 when $x(n) = -y(n)$ and $l = 0$. High negative correlation (−1) indicates high synchronization but one of the signals is inversed. High synchronization corresponds to value 1, whereas value 0 indicates lack of correlation. Cross-correlation function is sensitive to the direction of lag and may be used to identify time delays between the contractions in two time series. The cross-correlation functions were obtained using the xcov (equal to mean-removed cross-correlation) Matlab function. The maximum value of xcov gives the value of cross-correlation parameter.

2.2.2. The coherence function

The coherence function $Cxy(f)$ is the equivalent of the correlation in the frequency domain [11–17]. It is real-valued, positive and normalized to vary between 0 (no coherence) and 1 (complete coherence). For the two signals $x(n)$ and $y(n)$, $Cxy(f)$ is defined as follows:

$$C_{xy}(f) = \frac{|P_{xy}(f)|^2}{P_{xx}(f)P_{yy}(f)}$$

where $Pxx(f)$ and $Pyy(f)$ are the spectral density functions, $Pxy(f)$ is the cross-spectral density function.

A value of the coherence function near 1 is the sign of a linear relationship between signals x and y. For example, if two signals contain a sinusoid of the same frequency, there will be a peak in their coherence function at this frequency. By multiplying the mean of coherence values by 100 we get the coherence %.

To estimate coherence the following methods were used:

1. Matlab function cohere which is based on the Fourier transform [17,18].
2. MVDR—minimum variance distortionless response [19–21]. Here we applied the coherence_MVDR function, which had been written by Bonesty (http://www.mathworks.com/matlabcentral).

2.2.3. The wavelet cross-correlation and the wavelet coherence

In the case of the wavelet cross-correlation and the wavelet coherence analysis, discrete wavelet transforms of the uterine contraction signals were calculated. The signals were not filtered because the wavelet decomposition works like a band-pass filter. For this pair of detailed signals of which frequency band contained the dominant frequency the cross-correlation analysis and coherence analysis was performed [5,22–26].

3. Results

Fig. 1 demonstrates the Fourier analysis of the uterine contraction signals in the patient with endometriosis. Fundal and cervical signals were normalized and multiplied by hamming window. The values of the dominant frequencies, which are marked by the black dots, are very similar for these two signals. Fig. 2 shows how the time series shown in Fig. 1 are built from its approximation and details components. The level of performed discrete wavelet transform was 7. Because the detail signals at level 5 contain the dominant frequencies thus wavelet coherence and wavelet cross-correlation were calculated for D7 time series. For normal (or control) uterine contractions signals the dominant frequencies were the same and equalled 0.000293 Hz, thus the 9th level the DWT was performed and details D8 were taken into calculations. Fig. 3 illustrates the cross-correlation function (Fig. 3a) and the coherence functions (Fig. 3b and c) of the signals in the patient with endometriosis.

The results of application of the linear synchronization measures to the four pairs of typical uterine contraction signals are shown in Table 1. For each method, the values of synchroniza-