Application of wavelet coherence to the detection of uterine electrical activity synchronization in labor

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Abstract

This paper introduces the use of a method based on wavelet transform to detect the correlation between two uterine electrical activity bursts, recorded at different places on the pregnant abdomen during the same uterine contraction. The method used in this work is called wavelet coherence. The results of this study show that the wavelet analysis can successfully detect and quantify the temporal and spectral interactions between uterine bursts of electrical activity. They also indicate that the coherence is higher in the lower frequencies of the uterine electromyogram signal (EHG), and that it is possible to apply the method to non-segmented uterine signals. We find the method to give promising results permitting to evidence the coherence present in EHGs during a uterine contraction.

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1. Introduction

The aim of this study is to analyze the synchronization of uterine electrical activity by using the “wavelet coherence” method. This method allows us to obtain information about the coherence of different electrical activity bursts recorded at two separate positions on the uterus, in both time and frequency simultaneously.

Premature labor is one of the most important public health problems in Europe and other developed countries as it represents nearly 7% of all births. It is the main cause of morbidity and mortality of newborns. An early detection of preterm labor is important for its prevention, for example in insuring a better tocolytic drug efficiency. Continuous efforts are being made to...
find new biochemical or biophysical indicators of preterm labor risk [1]. One of the most promising is the analysis of the electrical activity of the uterus. Uterine electromyogram recorded externally in women, the so-called electrophysiologicalogram (EHG), has been proven to be representative of uterine contractility. The analysis of such signal may allow the prediction of a preterm labor threat as soon as 28 weeks of gestation (WG) [2,3].

The physiological phenomena underlying labor remain however badly understood. It is well-known that uterine contractility depends on the excitability of uterine myocytes but also on the propagation of the electrical activity to the whole uterus [2].

These two aspects, excitability and propagation, both influence the spectral content of EHG [2].

EHG is mainly composed of two frequency components traditionally referred to as Fast Wave Low (FWL) and Fast Wave High (FWH) [2]. These frequency components may be related to the propagation and to the excitability of the uterus respectively. It seems reasonable enough to assume that, if this is the case, a more intense coherence should be observed in the EHG signals for FWL (lower frequency component) than for FWH (higher frequency component). Recent studies on the early prediction of preterm labor have focused on the analysis of FWH or even simply of the higher frequencies of the EHG [3]. If the above hypothesis is correct, FWH being primarily related to the uterine cell excitability and FWL to the propagation, the mechanisms of coordination and organization of the uterus as a whole has still neither been fully understood, nor used for predicting preterm labor.

So far, the main method used for EHG propagation analysis has been linear inter-correlation. In reported work, the inter-correlation coefficients calculated on EHG envelope are usually good (∼80%) but the coefficients calculated on temporal signals are much lower [4,5]. This is however a low significance results, as even the inter-correlation of the envelope of uncorrelated noise gives very high correlation coefficients.

Marque and Duchene showed, by using correlation coefficient that the strongest correlation between bursts is at the low frequency component [6], i.e. FWL. Mansour et al. used the inter-correlation function to analyze the propagation of the uterine electrical activity on four internal electrodes, in the uterus of a monkey in labor [7]. The signals were first filtered in the frequency bands of the two waves, FWL and FWH. Then the inter-correlation function was calculated for each wave between the two pairs of electrodes. The result indicated that the inter-correlation coefficient is always higher for FWL than for FWH.

Inter-correlation is a temporal method; it cannot be used to analyze the interplay of various frequency components independently. To overcome this limit, the solution is to study the relationship between the uterine burst in the time-frequency domain.

Time frequency distributions (TFDs) were introduced as a means of representing signals whose frequency content is varying with time, and for which both time domain representations and frequency domain representations are inadequate to appropriately describe the signal. Many different TFD of a signal have been proposed, including, but not limited to, the Wigner-Ville distribution (WVD), the spectrogram using a Short Time Fourier Transform (STFT), the wavelet transform (WT), the Hilbert Huang transform (HHT) and other methods that evaluate several parameters with TFD, such as the relationship between the instantaneous frequency (IF) and the TFDs [8].

Several approaches have been taken to define the relationship between nonstationary signals in the time-frequency domain. The three main approaches are:

1. multiple window time frequency analysis (MW-TFA) [9];
2. frequency-dependant correlation coefficient [10];
3. time varying causal coherence function (TVCCF) based on the multivariate autoregressive model [11].

Below we will briefly describe each method’s advantages, disadvantages and applications in order to compare them with the method we chose to use in this work.

The first approach is the MW-TFA which has been a useful tool to estimate the TF distribution. As an extension of the Tomson’s MW method, Xu et al. demonstrated that the MW-TFA is able to estimate the TF coherence between two time series [9]. The method has been applied to investigate the temporal relationship between EEG signals from different brain regions. The authors compared the MW-TFA to the spectrogram in terms of TF distribution and showed that the MW-TFA representation is smoother (low variance). Another useful advantage of the MW-TFA is the ability to obtain TF coherence from one realization only, which is impossible with classical STFT approaches. As all windowing approaches, the method uses a constant window length which makes it not adaptive to the frequency characteristics of the signals.

The second approach was proposed by Ansari-Asl et al. who developed a novel estimator to evaluate the linear relationship between nonstationary signals in the time frequency domain [10]. The estimator is based on the computation of the Pearson Product-Moment correlation between EEG signals filtered in a narrow band and overlapping frequency bands using a continuous filter bank. The results show a good resolution in terms of time-frequency evolution of the relationship between two signals. The main problem with this approach is also the use of a constant window length.

The last approach is based on the modeling of the system under investigation by multivariate autoregressive or multivariate autoregressive moving average (MVARMA) model. The main advantage of this method is its possible simultaneous application for multichannel analysis, which is not the case with the two methods previously mentioned. For example, Zhao et al. proposed the estimation of a TVCCF by using a MVARMA model [11]. The method applied to blood flow data gave promising results and provide valuable insights into the composition of the physical structure of the renal autoregulatory system. The quality of the estimation depends however on the reliability of the fitted multivariate model. Indeed, all the necessary information is derived from the estimated model parameters, which are related to the choice of an optimal model order and an optimal epoch length.

In this work we chose to use the wavelet coherence due to its simplicity, the use of a variable window length depending on
the analyzed frequency band, and because it does not suppose a particular model of the data. In addition, the wavelet analysis has been used with success on many types of signals such as EEG signals [12] and geophysical time series [13].

2. Patients and methods

2.1. Signals

The real EHG signals used in this study are obtained from three women in labor. The measurements were performed by using a 16-channel multipurpose physiological signal recorder, most commonly used for investigating sleep disorders (Embla A10). Reusable Ag/AgCl electrodes were used. The measurements were performed at the Landspitali University Hospital in Iceland, using a protocol approved by the relevant ethical committee (VSN 02-0006-V2). The signals used were the bipolar signals Vb7–Vb8 (Fig. 1) corresponding to two channels on the median vertical axis of the uterus.

The signal sampling rate was 200 Hz. The recording device has an anti-aliasing filter with a low pass cut-off frequency of 100 Hz. The concurrent tocodynamometer paper trace was digitized in order to ease the identification of contractions. The EHG signals were segmented manually to extract segments containing uterine activity bursts.

2.2. Wavelet transform

The continuous WT (CWT) can decompose a signal into a set of finite basis functions. Wavelet coefficients \( W_X(a, \tau) \) are produced through the convolution of a mother wavelet function \( \Psi(t) \) with the analyzed signal \( X(t) \) or:

\[
W_X(a, \tau) = \frac{1}{\sqrt{a}} \int X(t) \Psi^* \left( \frac{t-\tau}{a} \right) dt
\]

where \( a \) and \( \tau \) denote the scale and translation parameters respectively, * denotes complex conjugation. By adjusting the scale \( a \), a series of different frequency components in the signal can be extracted. The factor \( \sqrt{a} \) is for energy normalization across the different scales. Through WT, the information of the time series \( X(t) \) is projected on the two-dimension space (scale \( a \) and translation \( \tau \)).

In this study, we used the complex Morlet wavelet, given by:

\[
\Psi_0(t) = \pi^{-1/4} e^{i \omega_0 t} e^{-\frac{1}{2} t^2}
\]

where \( \omega_0 \) is the wavelet central pulsation. In this paper, we used \( \omega_0 = 1 \). Morlet wavelet is a Gaussian-windowed complex sinusoid; the Gaussian’s second order exponential decay of the Morlet function gives a good time localization in the time domain [14]. We chose the complex Morlet WT (cMWT) as it provides the signal amplitude and phase simultaneously. This property allows us to use the cMWT to investigate the coherence/synchronization between two signals recorded at two different sites simultaneously.

Based on cMWT, the wavelet power of a time series \( X(t) \) at the time scale space is called the scalogram and is simply defined as the squared modulus of \( W_X(a, \tau) \).

2.3. Wavelet coherence

Given two time series \( X \) and \( Y \), their cMWT are \( W_X(a, \tau) \) and \( W_Y(a, \tau) \), respectively. Their product is defined as \( W_{XY}(a, \tau) = W_X(a, \tau)W_Y^*(a, \tau) \), where * means complex conjugation. The plot of \( |W_{XY}(a, \tau)|^2 \) is called coscalogram [12]. It provides a mean to indicate the coincident events over frequency, for each time in the signals \( X \) and \( Y \).

In this paper, we used the wavelet coherence that has the same form as the Fourier-based coherence function, namely the ratio of the cross spectrum to the product of the auto-spectrum of \( X \) and \( Y \). The definition of the wavelet coherence is written as:

\[
(C(a, \tau))^2 = \frac{|W_{XY}(a, \tau)|^2}{W_{XX}(a, \tau)W_{YY}(a, \tau)}
\]

With the coscalogram defined as:

\[
W_{XY}(a, \tau) = \frac{1}{a} \int_{-\Delta t}^{+\Delta t} W_X(a, \tau + t)W_Y^*(a, \tau + t)dt
\]

Note that the hermitian product defined above is replaced by an estimation given by an averaging over time \( (\tau \pm \Delta t) \).

The Auto-spectra \( W_{XX}(a, \tau) \) and \( W_{YY}(a, \tau) \) can be calculated by using the above equation. When using these definitions, the coherence is bounded between 0 ≤ (\( C(a, \tau) \))^2 ≤ 1.

3. Results

In the study, we applied the wavelet coherence method on a set of signals registered on three women during labor. The first step was the manual segmentation of the bursts of contractile activity. The segmentation was used to isolate the burst from the non-contractile parts of the signal (baseline). Then we first applied the method on the segmented bursts to detect their coupling or synchronization.
The scalogram (Fig. 2c and d) permits to identify the frequency components of the bursts X and Y. It clearly shows the two frequency components FWL and FWH. Fig. 2e presents the wavelet coherence between the same two bursts used above, recorded during the same contraction, from separate locations on a woman during labor. We can notice that the strongest correlation concentrates in the [0.1–0.3] frequency band, corresponding to FWL.

The second step of the study was to test the method on signals with no previous segmentation of the bursts. This was done in order to test the robustness of this method relatively to the baseline noise.

In the results shown on Fig. 3, we used two EHG signals, each one containing four bursts of activity. In the scalograms (Fig. 3b and d), we can observe the two frequency components (FWL and FWH) of each segmented burst.

Fig. 3e presents the result of the wavelet coherence between the two signals. We can notice strong coherence values during the activity bursts, and very small ones between the bursts (baseline).

This figure also confirmed that the strongest coherence is related to FWL. We can conclude from this observation that it is not necessary to segment the contractions before analysis. The wavelet coherence can successfully be used directly on the signal containing many bursts, as the baseline is completely

Fig. 2. Two electrohysterograms (EHG) bursts (a, b) and their respective scalograms (c, d), with the two frequency components, Fast Wave Low (FWL) and Fast Wave High (FWH), (e) wavelet coherence between the two segmented bursts showing the difference in coherence between FWL and FWH.

uncorrelated, opposite to the signal. This result could be of great importance and could ease the processing for clinical use.

4. Discussion

The characterization of the propagation of uterine electrical activity may provide information that could be of great importance for obstetrical purposes. A good characterization of this propagation would permit a better comprehension of the function of uterine contractile activity during pregnancy and labor and may lead to more sensitive predictors of preterm labor.

In this paper, we have presented preliminary results showing how uterine electrical activity synchronization can be studied by using wavelet coherence. This method can be used to detect the coupling between the uterine EHG bursts, as it respects the non stationarity of EHG signal and the non linearity of the propagation expected for uterine EHG. Wavelet coherence can successfully detect the correlations of EHG activity recorded at two different sites, and separate them clearly from the uncorrelated baseline noise recorded between bursts.

In brief, wavelet coherence can provide a new view of the correlation with respect to both the time and frequency characteristics of the EHG signal.

The results are encouraging but they only apply to three women during labor. The next step is to use signals recorded during pregnancy and labor for the same woman. By studying the synchronization longitudinally along term, we expect to be able to define the parameters related to propagation that are most likely to evidence the change from the no-coherent and inefficient contractions, during normal pregnancy, to the strong and organized contractions of labor.

5. Conclusion

This paper shows the power of the wavelet analysis in the study of the synchronization of uterine electrical activity. This method permits us to evidence stronger coherence between two bursts of electrical activity (segmented or not segmented) at the lower frequency component. This adds weight to the hypothesis that frequency components (FWL and FWH) are related to the propagation and to the excitability of the uterus respectively, without conclusively rejecting or confirming it. Further work is needed to test if this method is able to differentiate between inefficient un-propagated contractions, associated to normal pregnancy, and efficient propagated contractions recorded during labor. If so, it could be used to predict preterm labor.

Conflicts of interest

None.

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References


Fig. 3. Two electrohysterograms (EHG) signals (a, c) and their scalograms respectively (b, d), (e) wavelet coherence between the two EHG signals.


