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A multichannel time–frequency and multi-wavelet toolbox for uterine electromyography processing and visualisation

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ABSTRACT

The uterine electromyogram, also called electrohysterogram (EHG), is an electrical signal generated by the uterine contractile activity. The EHG has been considered a promising biomarker for labour and preterm labour prediction, for which there is a demand for accurate estimation methods. Preterm labour is a significant public health concern and one of the major causes of neonatal mortality and morbidity [1]. Given the non-stationary properties of the EHG signal, time–frequency domain analysis can be used. For real life signals it is not generally possible to determine a priori the suitable quadratic time–frequency kernel or the appropriate wavelet family and relative parameters, regarding, for instance, the adequate detection of the signal frequency variation in time. There has been a lack of a comprehensive software tool for the selection of the appropriate time frequency representation of a multichannel EHG signal and extraction of relevant spectral and temporal information. The presented toolbox (*Uterine Explorer*) has been specifically designed for the EHG analysis and exploration in view of the characterisation of its components. The starting point is the multichannel scalogram or spectrogram representation from which frequency and time marginals, instantaneous frequency and bandwidth are obtained as EHG features. From this point the detected components undergo parametric and non-parametric spectral estimation and wavelet packet analysis. Intrauterine pressure estimation (IUP) is obtained using the Teager, RMS, wavelet marginal and Hilbert operators over the EHG. This toolbox has been tested to build up a dictionary of 288 EHG components [2], useful for research in preterm labour prediction.

1. Introduction

Preterm birth accounts for some 10% of all births and is one of the most relevant obstetric conditions [1]. Despite the technological and scientific advances in perinatal medicine, prematurity is responsible for most of neonatal deaths [3]. It is also a leading cause of long-term neurological disabilities in children. Therefore, interventions for the prediction and the prevention of preterm birth are needed. Although various risk factors such as previous preterm births, infection, uterine malformations, multiple gestation and short uterine cervix in second trimester have been associated with this condition, its etiology remains unknown [4,5]. Most cases of spontaneous preterm birth are associated with an increase in the contractile uterine activity which can be related to internal uterine pressure (IUP) [6]. Tocography is currently a widely used method for measuring uterine pressure and can be either internal or external. The IUP, taken by invasive tocography, offers higher accuracy [7], but can only be used in labour with ruptured membranes, so it is inappropriate for preterm detection studies. The external tocography has the advantage of being non-invasive and easy to use. The main drawbacks are: (i) low accuracy, (ii) dependence on transducer position and maternal abdominal wall fat, (iii) limited conveyed information about contraction efficiency [8]. Actually it can be basically considered as a uterine contraction occurrence rate detector. Moreover, certain types of uterine contractile activities are not detectable by the tocogram while representing a preterm risk or foetus stress inducer [9]. Therefore, since its introduction in the clinical setup, tocography has not significantly contributed to the preterm labour characterisation and detection. In view of this, there has been an increased interest on the electrical signals called Electrohysterogram (EHG), due to the uterine activity as opposed to the mechanical uterine pressure measured by a Tocodynamometer. The EHG may become

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an alternative to conventional tocography in the evaluation of the uterine electrical activity and contribute to a better understanding of labour and preterm labour etiology. The electrical signal is recorded non-invasively from the maternal abdominal wall. The targets for electrohysterography are the preterm labour possible candidates, and patients for which a differential diagnostic between true and false preterm may lead to a reduction in the hospitalisation rate and tocolytic therapy [4]. Although the exact electrophysiological mechanisms behind the EHG generation are poorly understood yet; it is well-known that they are related to the uterine myocytes excitability and to propagation activity in the myometrium. These excitability and propagation are the basic elements of the EHG signal components which researchers are currently using in a quest to predict preterm labour as early as 28 weeks gestation [10,11]. Recently a physiologic multiscale model of the EHG has been studied which accounts for the principal ionic dynamics at the cell level and relative propagation [12].

Preterm reliable prediction methods have been much sought and EHG seems to be an adequate tool for this purpose [13–15], moreover this signal being non-stationary by nature has prompted researchers to use advanced signal processing methods [16–18].

The most important tools to deal with non-stationary signals such as the EHG have been time–frequency analysis and time-scale analysis (wavelets) which have led to the time and frequency characterisation and identification of the EHG components. In this paper, time-scale analysis will be referred by the general term time–frequency analysis. Regarding spectral analysis [19,20], the power spectral density methods based on the Fourier transform or averaged Fourier transform variations have been widely used [21,22], Wavelet packet decomposition (WP) and filtering was proposed for three different objectives: de-noising, EHG component detection and feature extraction [23,24]. In recent times, Wavelet Coherence has been used as a tool to detect correlation between uterine electrical activity bursts [25]. It has been found that strongest coherence exists in the Fast Wave Low (FWL) component. Furthermore, phase synchronisation, propagation velocity and direction are important parameters extracted from EHG which are used to distinguish between labour and normal pregnancy contractions [26–30]. Wavelet transform (WT) and Hilbert transform are two well-known methods to extract the phase information between signals [27,17,31–33], on the other hand, since conduction velocity and direction of the EHG is closely dependant on gap-junction connections between cells, some researchers prefer to use high density electrode setups in addition to using various estimation methods [34,35]. In [36] a comparative study has been presented for linear, nonlinear and bivariate parameters of the EHG in order to find out the most pertinent ones to discriminate between labour and pregnancy contractions. [36–38] It has been reported that selected nonlinear features perform better in this respect [26].

Regarding previous studies on the subject of this publication, time and joint time–frequency methods have been successfully applied to EHG signal [31,39,40,22]. However, research groups seem to use the time–frequency method that better suits their particular needs, and there has not been a report about a general tool that allows the user to perform and represent at once, several of these methods where considerations such as normalisation, readability and parameter selection have been taken care of. Moreover, spectral and time features estimation methods, lack a comparative tool for mutual evaluation and tentative standardisation. In [41] a software tool is presented which seems to be the only relevant report related to this work where features such as the power spectral density, wavelet marginals and ridges are obtained from a time frequency representation to provide EHG parameters with a strong database management strategy that aims to uniformisation and to improve compatibility between EHG signals of different sources. A limitation of this system is the impossibility of visualising the individual results for one subject recording and also the use of averaging that restraints the analysis of the outlier cases and signal time variation. Magnetomyography (MMG) recordings of uterine activity along with wavelet multiresolution analysis and the Hilbert transform have been used to successfully delineate EHG contractions [30]. Conduction velocity estimation using the MMG technique was developed by the same research group [29] with a quadrant-based approach that provided high spatial-temporal information of the EHG [28].

The motivation for the presented work arose from the lack of a software platform to put under the same roof, visualisation, detection and analysis tasks on the EHG components, simultaneously represented in an intuitive user friendly interface. The following tasks are performed for all channels up to 16: (i) user selected, temporal, frequency and joint time–frequency domain simultaneous representations, (ii) feature extraction from the time–frequency representation such as the marginals, localisation, instantaneous frequency and bandwidth, (iii) interactive selection of EHG components for posterior automatic characterisation through advanced signal processing methods, that include automatic signal pruning, frequency spreading and wavelet packet analysis, (iv) component spectral analysis using parametric and non-parametric methods, (v) IUP estimation using Teager, RMS, wavelet operators and Hilbert envelope. Most of the user parameters can be changed "on the fly". Also, the saved data structure is database compatible. This software tool has a modular architecture that permits future expansion.

2. Electrohysterogram components

The EHG signal is considered to be bounded between the *Slow Wave* (SW) and the *Fast Wave*, which, in turn, is divided in two bands: *Fast Wave Low* (FWL) and *Fast Wave High* (FWH) [11]. The SW is commonly related to skin stretching, abdominal and electrode movement. FWL is always present and shifts to higher frequency as pregnancy progresses. FWH is related to efficient labour contractions [11,42]. Within these bounds the main components are the following (only general properties are referred, the shown frequency bands are the reported furthest interval limits).

- *Braxton-Hicks*: long duration, strong amplitude, partial propagation to the uterine tissue typically present in the pregnancy. The frequency ranges from 0.4 to 0.84 Hz. Some authors [43] report the lower limit as 0 Hz.
- *Alvarez*: low amplitude and short duration, repeating at a rate of one or two per minute, duration around 0.5–1 min. The frequency content is reported to be higher than Braxton-Hicks, in the range of 0–1 Hz, localised in a small part of uterine tissue without propagation, detectable only by electrodes located near the relevant tissue area, might not be detectable by external tocography. It has been shown that it is related to an increased risk of premature labour [11,44,9,45].
- *Long Duration Low Frequency (LDBF)*: duration from 2 s to several minutes in a band from 0 to 1 Hz. Associated with hypertonia that corresponds to a steady uterine contraction without the necessary return to the muscle relaxation, whose prolonged action may induce partial hypoxia of the uterine tissue leading to foetus stress provoked by the compression of the blood supplying vessels.

The main EHG signal artefacts include:

- *Maternal ECG*: a strong component typically present in all the acquired channels, several higher frequency harmonics may be