Improvement of non-invasive intrauterine pressure estimation based on Electrohysterogram

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Abstract

Intrauterine pressure (IUP) signal is the "gold standard" for monitoring uterine contractions, whose main disadvantage is its invasiveness. Electrohysterography (EHG) is the measurement of uterine electrical activity that can be recorded at abdominal surface. Due to the relationship between electrical and mechanical activity of the uterine muscle, IUP estimations can be obtained using EHG parameters. Literature have reported Teager, root-mean-square (RMS) and non-normalized first moment as promising parameters for IUP estimation but estimation errors should be reduced. The aim of this study was therefore to improve intrauterine pressure estimations from surface EHG in women at active labor by optimizing signal bandwidth and window length of analysis. To perform this, IUP and EHG signals were recorded simultaneously from 10 women during active labor. RMS, Teager energy and unnormalized first statistical moment of the spectrogram were extracted from EHG signals in two bandwidths (0.2-1Hz and 0.34-1 Hz) and different window length (15s, 30s, 45s and 60s) for IUP estimation. The best result was obtained for a generalized model using Teager energy in the bandwidth 0.34-1Hz being the window length 30 seconds and achieving a value of RMSerror 9.52 ±2.57 mmHg which improves other reported results. This result supports the possibility of using EHG to estimate IUP, which would be very useful in obstetrics given the non-invasive nature of this technique.

1. Introduction

Monitoring uterine dynamics is essential to assess the progress of pregnancy and labor. Records based on pressure measurement are used in clinical setting. The gold standard is the intrauterine pressure measurement (IUP), which consists in the introduction of a catheter directly into the uterine cavity to detect pressure changes elicited by the presence of contractions. The invasiveness of this technique is its major limitation since it is required the rupture of membranes. In common clinical practice, pressure records are performed non-invasively using a tocodynamometer [1]. Surface tocography (TOCO) consists of placing a pressure sensor on abdominal surface to detect changes in abdominal contour as an indirect indication of uterine contraction. However this technique often experiences loss of contractions [1], is uncomfortable for the patient due to the use of tight straps and also the measurement could be affected by sensor position therefore repositioning of sensor may be required.

Since there is a relationship between electrical and mechanical activity, Electrohysterography (EHG) has emerged as an alternative technique for noninvasive monitoring uterine dynamics.[1]. It consists in the recording of uterine myoelectrical activity by placing contact electrodes on the abdominal surface. Besides the better performance compared to TOCO in detecting uterine contraction [1,2], it has been proven to provide additional information about uterine contractions efficiency which has been widely used, at research level, for preterm labor prediction [3], prediction of labor onset type (vaginal vs induced) [4], characterization of uterine myoelectrical response to labor induction drugs [2] among other applications. One of the factors that has limited its use in clinical context is that clinicians are not familiar with this signal and its interpretation but to traditional pressure records. Estimating IUP morphology and amplitude from EHG could on one hand overcome current limitations of pressure techniques (TOCO and IUP) to monitor uterine contractions and on the other hand facilitate the clinical use of EHG in obstetrics.

To date parameters from EHG signals, such as Teager energy [5], unnormalized first statistical moment [6] and RMS [7], have been computed for the IUP estimation. Although good correlations between estimated signals and IUP had been reported, the mean errors reported are greater than 13 mmHg. Therefore, the aim of this study was to improve the currently available methods for IUP estimation by analyzing different EHG signal bandwidths and assessing different window lengths for calculation of each EHG parameter.

2. Materials and Methods

2.1. Signal acquisition

The records were obtained from women who were in the active phase of labor, regardless of whether the labor has started spontaneously or has been induced, in Hospital Universitario y Politécnico de La Fe de Valencia. The study adheres to the Helsinki Declaration and was approved by the hospital ethics committee. All volunteers were informed of the nature of the study, the recording protocol and provided written informed consent. A total of 10 recording sessions were carried out and the recording time was between 1 and 4 hours per session. For each recording, the skin was carefully prepared using exfoliating gel (Nuprep, Weaver and Company, USA) to reduce skin-electrode impedance Subsequently, 8 monopolar disposable Ag/AgCl electrodes (red dot 2560, 3M, USA) were placed on the patient's abdomen (Figure 1): 3 electrodes in the supraumbilical zone, 3 electrodes in the subumbilical zone, 1 reference electrode in the right hip and 1 ground electrode in the left hip

The EHG signals were amplified and filtered in the range [0.1, 150] Hz using a custom made biosignal amplifier developed by the research group [8] and acquired with a sampling frequency of 500 Hz. Simultaneously, IUP signal was acquired by placing a pressure catheter directly into the uterine cavity, which is connected to a Corometrix 250cx series monitor (GE HealthCare, General Electric Company, USA) that acquires the IUP signal and sends the data to a Computer via serial port with a sampling frequency of 4 Hz. Both EHG and IUP signals were stored for subsequent analysis.

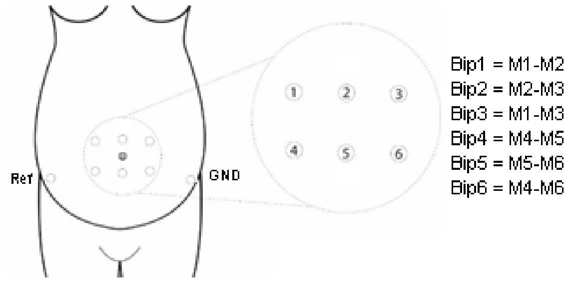

Figure 1. Electrode's arrangement for obtaining EHG records

2.2. Signal processing

Since the EHG signal energy is mainly distributed in the bandwidth between 0.1 and 4 Hz, EHG signals were band pass filtered and down-sampled (f_s) at 20 Hz to reduce the amount of data and computational cost. Then, bipolar signals were computed as indicated in the figure 1. The IUP estimation was performed on all bipolar signals. Nonetheless results are only shown for Bip3 since it usually presented the highest signal to noise ratio and best results.

Two different bandwidths (0.2-1 Hz and 0.34-1 Hz) were employed by filtering the EHG signal with a 5th order Butterworth filter and the cutoff frquencies were adjusted according to the bandwith analyzed. Additionally, four different moving (Δt=1/fs=0.25s) window lengths (K=15, 30, 45 and 60 seconds) were considered for the computation of the following parameters.

- ***Teager energy:*** consists in the calculation of the instantaneous energy. This energy is directly proportional not only to the square of the amplitude but also to the square of the frequency [9]. In the discrete time domain, the Teager operator can be defined as:

$$\Phi[n] = x[n]^2 - x[n+1]x[n-1] \tag{1}$$

Where $x[n]$ is the filtered signal in the corresponding analysis bandwidth

The secuence $TE(n)$ is obtained applying the moving average Teager energy over a $M = K{\cdot}fs$ samples interval.

$$\mathrm{TE[n]} = \left| \frac{1}{\mathrm{M}} \sum_{\mathrm{m}=-\mathrm{M}/2}^{+\mathrm{M}/2} \Phi\left[x[\mathrm{m}+\mathrm{n}]\right] \right|^{\frac{1}{2}} \tag{2}$$

- ***Unnormalized first moment (UNFM):*** is another method of estimating the IUP signal, which calculates the energy of the EHG signal from the spectrogram. The time-frequency representation of the signal EHG ($\rho\,[n,f]$) is calculated with a Hamming window $\omega\,[m]$.

$$\rho[n,f] = \left| \sum_{m=-\infty}^{+\infty} x[m]\omega[m-n]e^{-j2\pi f m} \right|^2 \tag{3}$$

Then, the unnormalized first statistical moment UNFM[n] is calculated by scaling $\rho[n,f]$ by its mean frequency f [5] in a selected frequency band (0.2-1Hz or 0.34-1Hz, depending on the analysis bandwidth)

$$UNFM[n] = \sum_{f_{min}}^{f_{max}} f \cdot \rho[n,f] \tag{4}$$

- ***RMS:*** consists in the calculation of the root mean square (RMS) value over a moving window of the EHG signal as follows:

$$RMS[n] = \left[\frac{\sum_{m=-M/2}^{+M/2} x[m+n]^2 \cdot r[m]}{\sum_{m=-M/2}^{+M/2} \omega[m]} \right]^{\frac{1}{2}} \tag{5}$$

where $r[m]$ is a rectangular window and M is the corresponding length of the rectangular window.

As mechanical activity is a direct consequence of electrical activity, the IUP is always delayed to respect of the electrical signal. This delay is corrected using the cross correlation function (CCF). The maximum value of the CCF gives us the time lag that must be adjusted. Finally, two approaches based on linear regression were performed to fit each EHG parameter sequence to IUP record. The first model corresponds to a linear fitting of the EHG parameter sequence of each patient to estimate the individual IUP record (individual model). The second model consists of a global fitting by previously concatenating IUP records of all patients to obtain a global estimation (global model). For each estimation, the root means square error (RMSe) was computed to assess the goodness of fit.

$$RMSe = \sqrt{\frac{\sum_{i=1}^{N}\left(IUP_i - \widehat{IUP}_i\right)^2}{N}} \tag{6}$$

Where IUP is the IUP recorded, $\widehat{IUP}$ is the IUP estimated from the EHG parameter and N is the number of samples of both IUP and $\widehat{IUP}$.

3. Results

Figure 2 shows the simultaneously recorded EHG and IUP signals. The IUP estimation using the three methods is from both individual and global model using the bandwidth between 0.2 and 1 Hz and a window length of 30 s. depicted in figure 3. It can be seen that all the three methods reproduce all contractions recorded in the IUP, although a greater variability in contractions intensity can be observed for UNFM method. Moreover, Teager and RMS-based IUP estimations do not differ substantially between individual and global model. While UNFM-based IUP estimation shows a greater difference between both approaches.

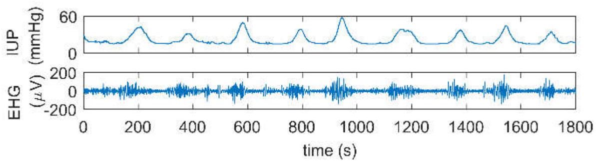

Figure 2. Simultaneous IUP and bipolar EHG (Bip3) recordings.

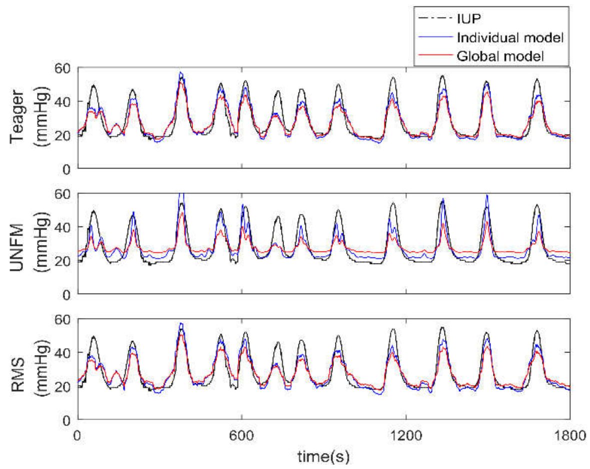

Figure 3. IUP and IUP estimated from the 3 methods calculated on bipolar record Bip3 using the bandwidth between 0.2 and 1 Hz and a window length of 30 s

Table 1 shows the mean and standard deviation of RMSe values for each estimation method, for each window length and for each analysis bandwidth for the individual model. Slightly lower values of RMSe are obtained in the bandwidth [0.2-1Hz] for all the proposed methods and window lengths. It can also be observed that the longer the window size the larger the error for RMS and Teager methods; whereas for UNFM 45s is found to be the optimal window. Comparing the best values for each EHG parameter, Teager-based and RMS-based provided very similar values (8.78 ± 2.14 mmHg and 8.79 ±2.05 mmHg, respectively) and about 1mmHg better than UNFM (9.77 ±2.48 mmHg).

Table 2 shows the mean and standard deviation RMSe values for the global model. Slightly higher error values were obtained for all estimations in the global models than those of individual models. In contrast to individual model, in most of the cases better values were obtained in the bandwidth [0.34-1Hz]. Regarding the window length, as in individual model, for RMS and Teager estimation methods the longer the window size the larger the error in most cases (with no remarkable difference between 15s and 30s). For the UNFM method, again the optimal window size is 45 s and RMSe values are higher than those obtained with the RMS and Teager methods.

Window length (s)	BW (Hz)	Teager	UNFM	RMS
15	0.2-1	8.78 ± 2.14	10.98 ± 2.24	8.79 ± 2.05
	0.34-1	8.94 ±2.34	11.39 ±2.41	9.04 ±2.32
30	0.2-1	8.94 ± 2.56	10.21 ± 2..39	8.99 ± 2.53
	0.34-1	8.94 ±2.54	10.58 ±2.43	9.06 ±2.58
45	0.2-1	9.87 ± 2.74	9.77 ± 2.48	9.92 ± 2.74
	0.34-1	9.89 ±2.73	10.15 ±2.48	10.02 ±2.77
60	0.2-1	12.01 ± 3.86	10.86 ± 3.54	12.06 ± 3.83
	0.34-1	12.22 ±3.76	11.40 ±3.33	12.33 ±3.72

Table 1. *RMSe values for each method of IUP estimation for individual model with different window length and analysis bandwidth.*

Window length (s)	BW (Hz)	Teager	UNFM	RMS
15	0.2-1	9.57 ± 2.29	12.02 ± 2.38	9.93 ± 2.34
	0.34-1	9.58 ±2.39	12.09 ±2.38	9.74 ±2.42
30	0.2-1	9.65 ± 2.64	11.41 ± 2.48	10.13 ± 2.76
	0.34-1	9.52 ±2.57	11.36 ±2.36	9.71 ±2.67
45	0.2-1	10.45 ± 2.76	11.06 ± 2.54	10.93 ± 2.92
	0.34-1	10.34 ±2.73	10.94 ±2.40	10.55 ±2.81
60	0.2-1	12.56 ± 3.85	12.18 ± 3.43	12.93 ± 3.95
	0.34-1	12.66 ±3.73	12.24 ±3.15	12.82 ±3.75

Table 2. *RMSe values for each method of IUP estimation for global model with different window length and analysis bandwidth.*

4. Discussion

Monitoring uterine contractions provides useful information during pregnancy and labor. Intrauterine pressure is the only reliable measure of uterine dynamics, from which not only the duration and frequency of contraction but also the tone and intensity of the contraction can be obtained. In the present study we assessed 3 previously reported methods for IUP estimation based on surface EHG parameters using different bandwidth and window length, being the best result obtained using Teager energy method: 9.52 ±2.57mmHg (BW:0.34-1Hz and window length: 30 s) in the global model and 8.78 ±2.14 mmHg (BW:0.2-1Hz and window length: 15 s) in the individual model. This result was considerably better than that obtained by Rooijakkers et al with this parameter (13.9±2.8 mmHg) using an scaling factor for each patient as the mean value of the optimized estimates for all the other patients [5]. Respect to the unnormalized first statistical moment of the spectrogram, the best result was achieved when using a window length of 45 s and the bandwidth 0.34-1Hz (10.94 ±2.40 mmHg). This estimation error is also smaller than that obtained by Rabotti et al (13.47±6.67 mmHg) and Rooijakkers et al.

(19.4±9.6 mmHg). Jezewski et al proposed [7] a RMS-based IUP estimation algorithm, and Rooijakkers et al [5] computed and reported RMSe values of 15.7±3.2 mmHg. Our RMS estimation of both global and individual model exhibit lower values than 10 mmHg for both analysis bandwidths when using windows length of 15 and 30 seconds. Even databases are different, all this indicate that our result shows a substantial improvement to those of the literature [5–7]. This improvement could be explained due the different bandwidth considered and electrode position which can result into a better SNR. In the literature the EHG signal is band pass filtered between 0.3-0.8Hz for computation of Teager and UNFM using a window length of 30s and 70s respectively, while for RMS, the EHG signal is band pass filtered in the range [0.05-5 Hz] with a window length of 60 s. 98% of uterine electrical activity occurred in frequencies less than 1 Hz [3], therefore we considered the two bandwidths [0.2-1Hz] and [0.34-1 Hz] which appear to be more appropriate as we obtain lower RMSe values. Based on clinical usefulness, results of global model have more generalization impact, therefore we conclude that the best analysis bandwidth is 0.34-1Hz and the optimal window length is 30s. The improvement is also enhanced due to a better electrode configuration that allow to capture a greater area of uterine activity. Moreover, we do not remove IUP basal tone, as literature does, as it supposes loss of information.

Although our results show an improvement to those of literature, is not exempt of limitations. First, a large inter-patient variability in the amplitude of the EHG signal has been observed without observing large differences in the intensity of contractions in the IUP record. Differences in body constitution, or obstetrical factors may be responsible of this variability. Second we use a linear model to reproduce a non-linear physiological process. Lastly, this and all reported studies are bipolar single-channel IUP estimations. That is, only the local information sensed with two electrodes is considered, whereas intrauterine pressure is a consequence of a global phenomenon of the entire uterus. Therefore, to reduce estimation error, further approaches can be explored such as introducing the obstetrical information of patients, performing multichannel and/or multivariable linear and nonlinear models and compensating the EHG's inter-patient differences.

5. Conclusion

In the present study, linear regression models were used to perform IUP estimations from EHG signal using two analysis bandwidth and different windows lengths. Results of this work point out that the best estimation method was achieved for Teager in the bandwidth 0.34-1Hz and the optimal window length was 30 seconds achieving an RMSe value of 9.06 ±2.58. Results outperformed those reported in the literature even for a global model. The proposed EHG-based technique could be suitable to monitor uterine dynamics in clinical conditions.

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References

[1] Euliano TY, Nguyen MT, Darmanjian S, McGorray SP, Euliano N, Onkala A, et al. Monitoring uterine activity during labor: a comparison of 3 methods. Am J Obstet Gynecol 2013;208:66.e1-66.e6. doi:10.1016/j.ajog.2012.10.873.

[2] Benalcazar-Parra C, Montfort-Orti R, Ye-Lin Y, Alberola-Rubio J, Perales Marin A, Mas-Cabo J, et al. Characterization of Uterine Response to Misoprostol based on Electrohysterogram. Proc. 10th Int. Jt. Conf. Biomed. Eng. Syst. Technol., SCITEPRESS - Science and Technology Publications; 2017, p. 64–9. doi:10.5220/0006146700640069.

[3] Fergus P, Cheung P, Hussain A, Al-Jumeily D, Dobbins C, Iram S. Prediction of Preterm Deliveries from EHG Signals Using Machine Learning. PLoS One 2013;8. doi:10.1371/journal.pone.0077154.

[4] Alberola-Rubio J, Garcia-Casado J, Prats-Boluda G, Ye-Lin Y, Desantes D, Valero J, et al. Prediction of labor onset type: Spontaneous vs induced; role of electrohysterography? Comput Methods Programs Biomed 2017;144:127–33. doi:10.1016/j.cmpb.2017.03.018.

[5] Rooijakkers M, Rabotti C, Guid Oei S, Aarts RM, Mischi M. Low-complexity intrauterine pressure estimation using the Teager energy operator on electrohysterographic recordings. Physiol Meas Phys Eng Med Physiol Meas Physiol Meas 2014;35:1215–28. doi:10.1088/0967-3334/35/7/1215.

[6] Rabotti C, Mischi M, van Laar JOEH, Oei GS, Bergmans JWM, Andrieux J C, Feix M R, Mourgues G, Bertrand P IB and NVT, et al. Estimation of internal uterine pressure by joint amplitude and frequency analysis of electrohysterographic signals. Physiol Meas 2008;29:829–41. doi:10.1088/0967-3334/29/7/011.

[7] Jezewski J, Horoba K, Matonia A, Wrobel J. Quantitative analysis of contraction patterns in electrical activity signal of pregnant uterus as an alternative to mechanical approach. Physiol Meas 2005;26:753–67. doi:10.1088/0967-3334/26/5/014.

[8] Prats-Boluda G, Ye-Lin Y, Bueno Barrachina JM, Senent E, Rodriguez de Sanabria R, Garcia-Casado J. Development of a portable wireless system for bipolar concentric ECG recording. Meas Sci Technol 2015;26:75102. doi:10.1088/0957-0233/26/7/075102.

[9] Kaiser JF. On a simple algorithm to calculate the "energy" of a signal. Int. Conf. Acoust. Speech, Signal Process., IEEE; 1990, p. 381–4. doi:10.1109/ICASSP.1990.115702.